Implant materials for knee and hip joint replacement: A review from the tribological perspective.

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Abstract. The hip and knee joints work under boundary/mixed lubrication during sleep and rest which causes starved lubrication by the natural lubricant synovial fluid and with the passage of time leads to arthritis resulting from the wear of joints due to starved lubrication. The excessive wear leads to loosening of joint needing total joint replacement. The current materials used in total knee replacement and total hip replacement are presented in this paper. Biomedical implants are gaining increasing attention nowadays to improve the working lifespan of joint replacements like hip and knee. Researchers are focussing on developing biocompatible materials with improved wear resistance for joint replacements. Various biocompatible metals and polymers have been used for knee & hip joints which are discussed in this paper. The investigations on self-lubricating biocompatible coatings on metals and alloys are the current focus of research. In this paper, a broad review of the materials used for total joint prosthetics is presented and the current trends of the joint replacement technology are discussed besides highlighting the various issues and challenges.

1. Introduction
Knee and Hip joints are the largest synovial joints present in the body. Nearly whole body weight of an individual is supported by these joints and so these joints are most vulnerable to acute injury and osteoarthritis [1]. The need for total joint replacements arises due to several reasons which include arthritis, and accidental injuries. Arthritis is marked as one of the major orthopaedic problems in the world. The data given by “centre for disease control and prevention” showed an estimated 54.4 million arthritis patients in US alone. It is reported that arthritis itself affects about 15% of population i.e. more than 180 million people [2]. More than 100 forms of arthritis are reported at present [3]. Among these, two major form of arthritis are very commonly found: they are osteoarthritis and rheumatoid arthritis. In osteoarthritis, the cartilage of the joint is affected, which results in a decrease in its elasticity. When the cartilage becomes stiff, it increases the chances of getting damaged. The cartilage of the joint acts as a shock absorber, which gradually wears away in hip and knee joints. The damaged cartilages & ligaments become stretched, which results in pain and eventually leads to bone on bone contact in the joint, causing severe pain. This form of arthritis usually affects elderly patients. Rheumatoid arthritis is an inflammatory form of arthritis. It is commonly found in women, who are in the age group of 40-60 years. In this the synovial membrane is affected, causing swelling and pain in the joint. If this form of arthritis is not treated, it can lead to the deformity of the affected joint [4]. Patients suffering from both forms of arthritis stand to benefit from total joint replacement. Accidental injuries may also lead to the need for joint replacement. Depending on the type of fracture and the amount of bone loss to the joint, during an accident, joint replacement or joint arthroplasty may be required. Total hip and knee joint replacement is one of the most significant research fields of orthopaedics. The use of implants came forth in the late 19th century followed by the first half of the 20th century. During this period, the implants which were inserted, resulted in failure due to their improper design, lack of wear and corrosion resistance. Thus it became necessary to use metals and ceramic with biocompatibility as their main property. These materials provide implants which can
The use of biomaterials is assessed by their physical, mechanical, tribological, biological and chemical properties. The biomaterials which are used in implants should be induced in the body in such a way that these do not cause toxicity in the host body. The debris, generated due to wear of implants, and corrosion products, developed due to oxidation, are toxic and may result in genetic damage [6]. The wear and corrosion behaviour of implants are influenced by various factors, which include the material composition, biological surroundings like oxygen, pH, temperature etc. Variation in these factors may affect the amount of metal ion particles released from the metallic implants. Biocompatibility plays a vital role in biomaterials used for total joint replacements. The choice of implant, which is induced in the host, should provide a replacement to different properties which are present in the bone material like modulus of elasticity, strength, hardness etc. For remodelling of the bone, we need to evaluate the biomechanics of the bone, which is to be replaced by the implant. This article reviews the biomaterials used for knee joints. One of the most important factors affecting the use of implant material is their wear and corrosion behaviour in the biological environment. This article also reviews the implications of these considerations in more detail.

2. Biomedical implant materials

The ultra-high molecular weight polyethylene (UHMWPE) and metallic biocompatible materials like stainless steel, cobalt based alloys and titanium based alloys have sufficiently gained ground as suitable candidates for total joint replacement. These are discussed in the following sub-sections.

2.1. Medical grade Stainless Steel

Commonly used material for joint replacement is 316L stainless steel, even though other stainless steel materials like 316LVM stainless steel, ASTM F-55, F-138 and F-139 are also available. Medical grade 316L stainless steel has been used for decades in the field of orthopaedics as medical implant and mostly for total joint replacements, due to its low cost and high strength. Its excellent biocompatibility makes it the material of choice for joint replacements. Its resistance to various corrosive agents is due to presence of 12% Cr that helps it in formation of an adherent corrosion resistant coating of the oxide, Cr2O3. This helps it in performing a self-healing process [7]. To increase the life and corrosion resistance of 316L stainless steel, researchers use different coatings which are deposited using various coating techniques. A research was carried out in which sol-gel alumina composite coatings were deposited on AISI 316L stainless steel which resulted in better corrosion resistance [8]. In another research, the corrosion resistance of an appropriate ceramic coating was studied. The coating of appropriate thickness was deposited on 316L stainless steel providing the best corrosion protection [9]. A research work was carried out in which the two-four- and six-layer coating of aluminium oxide was deposited by sol-gel technique on 316L stainless steel, which resulted in the improvement of corrosion resistance. This work shows an application of sol-gel technique which can be used to obtain an amorphous aluminium oxide coating on AISI 316L stainless steel. Due to cost efficiency and success of AISI 316L stainless steel for many decades, it is still the material of choice for researchers [10]. A work was carried out in which a double layer coating of bio glass-silica was deposited on 316L stainless steel which helped to provide a link between the coated materials and the bone. This in turn prevented the corrosion of medical grade implant in body fluids [11]. A modification of the surface of AISI 316L stainless steel was carried out with bio-glass hydroxyapatite by using laser engineered net shaping manufacturing process technique. The experiments revealed that the thickness, hardness & the microstructure of the modified surface can be controlled by controlling the laser parameters [12]. In another work, the researcher used cold spray process for depositing powder of Co-Cr and stainless steel on medical grade 316L stainless steel, which helped to improve the strength and corrosion resistance of the 316L stainless steel, for biomedical applications [13].

2.2. Cobalt-based metallic alloys

Cobalt-based alloys are known for their high corrosion resistance. They obtain this resistance by
forming an oxide layer even in the non-ideal body environments [14], [15], [16]. Addition of molybdenum to cobalt-based alloy has proven beneficial as it provides resistance to the alloy even in corrosion active conditions, which are named as hydrochloric conditions. The fatigue and corrosion resistance of cobalt-based alloys are superior to that of stainless steel. Even though fatigue fracture remains a possible threat in cobalt-based alloys, but the corrosion product of Cr-Co are more toxic than those of 316L stainless steel [17]. Cobalt alone cannot be useful, as it has not shown good results with cells in-vitro study. In a work, it is stated that cobalt alone was found toxic to cell lines and inhibited the growth and production of type-I collagen, alkaline phosphate, and osteocalcin. However, chromium and cobalt–chromium were tolerated by cell lines, producing no cytotoxicity. Thus, the result of their study showed that metal debris can affect the growth of osteoblast cells in vitro [18].

Even though cobalt-based alloys are known for their corrosion resistance; even then researchers are using different coating techniques for deposition of different material films to increase the corrosion resistance of this metal alloy. This helps in increasing the life of an implant. A multilayer film on cobalt chromium molybdenum (Co-Cr-Mo) substrate by magnetron sputtering technique was used to obtain corrosion resistance in several simulated body fluids where a normal body temperature was used. The results showed the corrosion resistance was obtained at a specific deposited layer thickness [19]. A hard DLC coating and nitrogen ion implantation on cobalt-based alloy was used to reduce the wear of UHMWPE which helps to increase the life of the implant. An improvement in the wear behaviour of UHMWPE was achieved when used against different coated metal alloy in their study. This study also signifies the importance of DLC coating and ion implantation on cobalt chromium in the manufacturing of knee implants [20]. A research was carried out in which the researcher deposited an electrolytic aluminium oxide coating on Co-Cr-Mo for hip implant, in order to increase its performance. The results from their study showed wear loss of UHMWPE to the coated surface is eight times less than that of the uncoated surface [21].

Minimizing friction and wear in the artificial joints is a contemporary problem faced by researchers. The conventional joint replacements are made from Co-Cr-Mo alloy and UHMWPE. Co-Cr-Mo constitutes the femoral component, whereas UHMWPE constitutes the tibial component. The author points out that the main disadvantage of this type of joint is the wear and tear of UHMWPE. For the other component, the allergic potential of the Co-Cr poses a disadvantage. The wear of UHMWPE is one of the most significantly occurring problems in the prosthetic joint industry and the author has readily acknowledged the problem [22].

2.3. Titanium-based metallic alloys

Titanium implant manufacturing was started in the late 1930’s. Titanium-based alloy implants are one of the most popular and important options for total joint replacements for knee and hip joints. Titanium and its alloys are mostly used in the field of orthopaedic implant industry for biomedical applications. Ti–6Al–4V is one of the high strength and corrosion resistance alloys among the titanium alloys. Its corrosion resistance is due to the formation of an adhesive layer of TiO2 film which is formed on the alloy surface. TiO2 is thermodynamically stable in the pH range between 2 and 12, this property makes it the more important metallic material in the field of orthopaedics [23]. Despite great properties, researchers are working on titanium-based alloys to increase its life by minimizing the corrosion and wear of titanium implants. A bio-tri-bio-corrosion of titanium alloy in a simulated body fluid for biomedical application was carried out. This work was done by using an electrochemical technique, which shows the alloying elements like Al and V in titanium-based biomaterials considerably reduce the wear accelerated corrosion under tribo-corrosion conditions [24]. A study was carried out, in which friction and wear properties of an ion implanted titanium alloy against UHMWPE was examined. In this study, it was seen that the friction coefficient was decreased by five times in wet-ability environment and the wear resistance of UHMWPE increased by forty times against the ion implanted titanium alloy [25]. To increase the strength of titanium-based alloys, researchers are trying different materials which can be used for the coating. A coating of functionally graded Co-Cr-Mo was deposited on titanium alloy structure, after the coating was deposited, an in-vitro biocompatibility test was performed with living cells to see the compatibility of this deposited coating. Laser engineered net shaping (LENS) technique was used for deposition of coating on the titanium alloy. The tests were done under maintained body temperature of 37oC. The coatings, which
Failure of PTFE in vivo cells,

UHMWPE was introduced. Gamma irradiated UHMWPE showed increase in wear,

du ty, and surface is oxidized.

Surface is oxidized against surface, which shows its increase in wear process of oxidation takes place in joint arthroplasty, it affects the longevity of the UHMWPE due to the wear process. It has been observed that gamma UHMWPE undergoes oxidation process, which shows its increase in wear, resulting in decreasing mechanical properties. A research was carried out, which disclosed that vitamin E-stabilized UHMWPE showed improvement under oxidation process while maintaining wear resistance and fatigue strength. This resulted in good mechanical and wear properties in joint arthroplasty. The vitamin-E-stabilized and irradiated UHMWPE are clinically used, resulting in improving the performance compared to older materials in total joint replacement technology [35].
3. Challenges against corrosion of implants

Besides biocompatibility, we also take into consideration the wear and corrosion resistance of the materials used for joint replacements. Apart from biocompatibility, these materials should have other durable properties which will be useful for total joint replacements, which include the mechanical properties of these biomaterials. Metals and metal alloys are used for biomedical applications from decades, now biomaterials are also made of polymers, and composites which are used in the orthopaedic industry [36]. The biomaterials used in total joint replacements face a challenge due to the process of different kinds of corrosion-causing infections which result in total joint replacement surgery. Researches are being carried out by several academic institutions in order to minimize the process of corrosion which will help in increasing the life of the implant used in joint replacements. When we talk about the corrosion of implants, the human body itself plays a vital part in providing the corrosive environment for these implants. The corrosion caused by the process of oxidation takes place with the body fluids interacting with the joint prosthesis. In living beings, we are well aware of the fact that the cells present in the body react when a foreign body is induced in it, which results in several reactions. In case of implants, corrosion takes place as a reactant product in the body of the living being. Human blood plasma is composed of Na+, K+, Mg2+, Ca2+, Cl-, HCO3-, HPO42-, SO42-. We understand that when the foreign body, in the form of an implant, is induced in the human body, it reacts with some of the fluids at its desired temperature of 37oC. From the literature, we know the environment of blood plasma shows aggression for many metals and alloys, which is due to the presence of a good concentration of chloride ions proving supportable environment for localized corrosion [37]. A study was carried out in which the author showed the corrosion resistance of Ti-6Al-4V alloy was significantly lower in the joint fluid when compared to urine and serum [38]. We know the pH value of a normal human body fluids is 7.4, but when an implant is induced the pH value decreases to 5, which is recovered to its normal range within a few weeks. On the other hand, it is known from the studies that decrease in pH value of body fluid results in the corrosion behaviour of metals [39], [40].

4. Conclusion

Biomaterials for orthopaedic technology are facing crucial challenges like improving corrosion and wear resistance and biocompatibility, to increase the life of implants. So, it has drawn the interest of biomaterials researchers, material designers and bio-tribologists in the recent years. This study reviewed the tribological properties and corrosion behaviour of some currently used biomaterials for total joint replacement. We discussed some important research investigations done for improving the wear and corrosion resistance of biocompatible materials used for implants. In this review, we also explored different coatings which provide wear and corrosion resistance to metallic biomaterials. No doubt, extensive research has been conducted for improving the performance of biomaterials for implants, yet research is still on to obtain a biomaterial having exceptional biocompatibility, high strength, good corrosion and wear resistance. Moreover, the in-vitro testing of biomaterials for implants gives us an idea of the materials behaviour and not the actual behaviour of materials in the body environment, i.e., there is a need to develop some in-vivo testing procedures for testing biomaterials for implants.

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