iJRASET
International Journal For Research in Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 4 **Issue:** II **Month of publication:** February 2016

DOI:

Volume 4 Issue II, February 2016
ISSN: 2321-9653
International Journal for Research in Applied Science & Engineering Technology (IJRASET)

Wear Analysis of Hip Joint Prosthesis: A Review

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Abstract: Total hip replacement (THR) is one of the most successful applications of biomaterials in the medical industry. In THR, a spherical head connected to the femoral stem articulates against a spherical cup/liner attached to the pelvic bone. The tribological performance of artificial hip joints is a critical issue for their success, because adverse tissue reaction to wear debris causes loosening and failure. The wear of the bearing surfaces of hip joint prostheses is a key problem causing their primary failure. Many studies on wear of hip prostheses have been published in the last 10 years. Theoretical/ numerical models have been proposed for investigating geometrical and material parameters also. This detailed study of wear analysis of hip joint is carried out highlighting anatomy of hip joint, wear and artificial implants such as hard on hard and hard on soft implants for hip joint. It aims to obtain in depth understanding of wear of bearing couples of artificial hip joint due to varying contact stresses under physiological gait loading.

I. INTRODUCTION

The aim of this article is to study the wear of bearing couples of hip joint prosthesis such as hard on hard, hard on soft implants due to varying contact stresses under physiological gait loading. Removal of material from one or both of the two solid surfaces in relative motion (sliding, rolling or impact) is termed as wear. Surface damage to material displacement with no net change in volume or weight is called as wear. Wear is related to interactions between surfaces and more specifically the removal and deformation of material on a surface as a result of mechanical action of the opposite surface. It occurs as natural consequence and mostly through surface interactions at asperities. It is a system response and not a material property. Interface wear is strongly dominated by operating conditions. Wear can be either desirable or undesirable. Desirable cases of wear include machining, polishing, shearing and writing with a pencil whereas undesirable cases include almost all machine applications such as bearings, cams and seals [10]. Wear takes place either by a mechanical process or by a chemical process or by combination of both and generally accelerated by thermal processes.The hip joint, scientifically referred to as the acetabulofemoral joint, is the joint between the femur and acetabulum of the pelvis and its primary function is to support the weight of the body in both static (e. g. standing) and dynamic (e. g. walking or running) postures. The hip joints are the most important part in the retaining balance. It forms the primary connection between the bones of the lower limb and the axial skeleton of the trunk and pelvis. Both joint surfaces are covered with a strong but lubricated layer called articular hyaline cartilage. It is a special type of spheroidal or ball and socket joint where the roughly spherical femoral head is largely contained within the acetabulum .The acetabulum grasps almost half the femoral ball, a grip augmented by a ring-shaped fibro cartilaginous lip, the ace tabular, which extends the joint beyond the equator. The head of the femur is attached to the shaft by a thin neck region that is often prone to fracture in the elderly, which is mainly due to the degenerative effects of osteoporosis. The pelvic inclination angle, which is the single most important element of human body posture, is adjusted at hips .The acetabulum is oriented inferiorly, laterally and interiorly, while the femoral neck is directed superiorly, medially, and interiorly.[14] The commonest cause of hip joint damage is simple wear and tear, when the lining of the joint (the cartilage) starts to wear away. This is known as osteoarthritis of the hip joint. This usually occurs spontaneously, but may also be as a result of previous injury or problems with the joint. The lining of the joint may also be damaged by a number of other medical conditions, such as rheumatoid arthritis or childhood hip problems. Because the hip joint is located deep in the groin, pain from hip damage is often felt at one or more of a variety of sites, including the buttock, groin, side or front of the thigh, the knee and occasionally as far as the front of the shin. Sometimes the pain is only felt in the knee, even though the hip is the cause of the problem. This is called ‘referred pain’. If the joint is worn and damaged, there are a number of things that can be done to minimize any pain or stiffness. Hopefully, with these measures, surgery can be put off for many years, or may never become necessary. It is only when people have pain or immobility that is seriously affecting their quality of life, despite these measures, that surgery should be considered .[15]

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ISSN: 2321-9653

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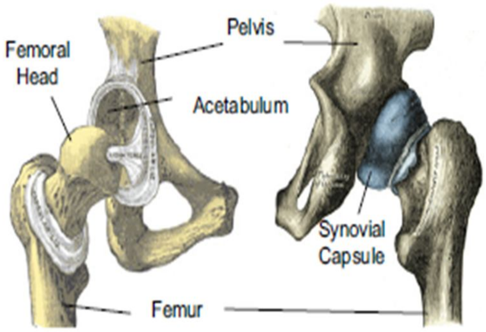

Fig 1: Anatomy of the hip joint [2]

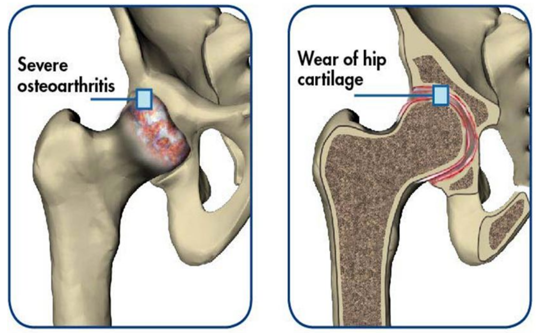

Fig. 2: Hip joints wear [12]

II. LITERATURE REVIEW

The wear of the bearing surfaces of hip joint prostheses is a key problem causing their primary failure. Substantial research on hip prostheses has been carried out to understand and evaluate their preclinical and clinical performance in terms of contact stresses, friction and wear, and mechanical reliability. As an important performance index of hip joint prostheses, wear progression of the bearing surfaces must be understood accurately. Previously both clinical and laboratory studies attempted to measure the wear of the implants to assess their performance. For instances essneretal carried out hip simulator tests using as simplified loading cycle, and compared and statistically analyzed the wear on ceramic-on-PE, metal-on- metal and ceramic-on-ceramic hip joint prostheses for a short period of time up to 5 million cycles. Such in-vitro tests are usually time-consuming and costly, which is especially the case when a comprehensive understanding on the roles of many design parameters is needed. The finite element method (FEM) as a powerful computational tool has been widely used to improve the design of hip joint prostheses and to minimize the expensive experimental trials. M.S.Uddin, L.C.Zhang carried out a comprehensive finite element analysis of the contact stress and wear in hard-on-hard hip joint prostheses under 3D physiological gait loading in walking cycles. This study aims to obtain an in-depth understanding of the wear of hard-on-hard bearing couples (PCD-on-PCD, ceramic-on- ceramic and metal-on-metal of total hip replacements). It was found that due to the gait motion, the intensity and location of the maximum contact stress in the bearing components change with the gait instances. With a given geometry and gait loading, the linear and volumetric wear on the cup surface increases with the number of gait cycles. With increasing the gait cycles, the surface wear can bring about scattered contact pressure distribution. Compared to the ceramic-on-ceramic and metal-on-metal couples, the PCD-on-PCD bearing has the lowest wear progression. It was also concluded that the computational wear model presented in this paper can reasonably predict the wear evolution in hard-on-hard hip implant [1]. The review of the main lubrication and wear models of hip implants published in the last few years has been carried out. An accurate description both of methods and results is reported, stressing simplifying hypothesis and models input data to make their comparison easier. One of the most significant findings that comes out from this study is that, although lubrication and wear are two different aspects of the same tribological scenario, they are modelled completely neglecting each other. Lubrication models do not consider the 3D topography of the articulating surfaces as well as the asperity contact and surface evolution caused by mixed and boundary regimes; on the other hand wear models simulate only dry contact. These limitations underline the difficulty of a realistic theoretical description of the hip implant tribological behavior, increased by the complex model solution, which need to cross use several numerical approaches. The present review can be useful to compare different wear and lubrication models and their results in order to evidence their reliability and limits and consequently plan specific studies for improving theoretical modelling that can help in the development of hip implants with higher performances and longer life. As general conclusion, it can be pointed out that both in lubrication and wear a distinction is made between models for soft-on-hard material couples, mainly MoP,and hard-on-hard implants, as MoM or CoC. The former are modelled in lubrication by means of a ball-in-socket configuration, and the elastic deformation, as well as wear, is attributed to the plastic element [2]. The distribution of contact pressure in the natural and artificial human joints is an important factor which affects the function of the joint. The contact pressure distribution on the hip prosthesis bearing surface is of special interest because it evinces the regions with high stresses. Numerous papers show the clearance between the two articulating surfaces plays an important role in the friction and wear processes taking place in the prosthesis. This paper presents a semi-analytical method to compute the contact pressure, friction torque, friction energy, and wear loss for soft-on-hard hip implants [3]. Many investigations have been conducted, using the FEM, to understand the contact stresses, deformation, damage and failure of the prostheses. Ahmet C.Cilingir performed Finite Element

(FE) study to investigate the contact mechanics and stress distribution of Ceramic-on-Ceramic (COC) hip resurfacing prostheses. It was focused in particular on a parametric study to examine the effects of radial clearance, loading, alumina coating on the implants, bone quality, and fixation of cup-bone interface. It was found that a reduction in the radial clearance had the most significant effect on the predicted contact pressure distribution among all of the parameters considered in this study [4]. The most complete database for loading conditions is due to Bergman et al. [5], who measured hip forces in nine daily activities, e.g. slow/normal/fast walking, walking upstairs/ downstairs, standing up/sitting down a chair, etc. While many authors reported hip contact forces, kinematic data as hip angles variation and angular velocities are not easily available [5].Computational wear modeling based on the Archard wear equation and finite element contact analysis was developed in this study for artificial hip joints and particularly applied to metal-on-metal resurfacing bearings under simulator testing conditions to address this issue. The computational prediction of the volumetric wear and the wear geometry agrees well with that of the simulator tests. The simulation demonstrates the progression of the wear geometry on both the cup and head. Metal-on-metal (MOM) hip replacements avoid the problem of polyethylene wear debris induced osteolysis and have been extensively researched and developed in the past decade. This study shows that a significant increase in wear area results in a corresponding increase in contact area, and consequently a significant reduction in contact stress, and the contact stress distribution is varying significantly in the worn region, particularly, the larger contact stress being generally distributed along the boundary of the worn zone Computational wear modeling has been widely considered not only for mechanical systems but also for biomedical products such as artificial hip prostheses. Among these studies, Archard's wear law has been commonly adopted because of its simplicity and wide applications. One of the successful computational wear models was pioneered by Maxian et al. (1995), focusing on a total hip composed of a metallic femoral head articulating with polyethylene acetabular cup [6]. Hip joint simulators have been largely used to assess the wear performance of joint implants. Due to the complexity of joint movement, the motion mechanism adopted in simulators varies. The motion condition is particularly important for ultra-high molecular weight polyethylene (UHMWPE) since polyethylene wear can be substantially increased by the bearing cross-shear motion. Computational wear modelling has been improved recently for the conventional UHMWPE used in total hip joint replacements [7].

III. HIP JOINT PROSTHESIS

A. *Artificial Hip Joint*

Despite its remarkable characteristics, the hip joint can be affected, more often in aged people, by chronic pain and diseases such as osteoarthritis, rheumatoid arthritis, bone tumors or traumas. In these cases, the best clinical solution is the total hip arthroplasty, a surgical procedure that replaces the unhealthy hip joint with an implant, preserving the synovial capsule. Nowadays about 200,000 and 80,000 interventions/year are performed in the USA and in the UK, respectively, and they are estimated to increase of about 170% by 2030. Although hip arthroplasty is considered one of the greatest achievements in orthopedic surgery in the last decades, from an engineering point-of-view hip implants are not a complete success and still need further developments. In particular they tend to have a limited service life of about 15 years, which is not satisfactory for patients under 60 years of age, about the 44%, demanding a life expectancy in excess of 20 or 25 years. For these patients, an alternative and less invasive resurfacing technique has recently gained new interest. In this approach the bearing couple of the total replacement implant is maintained, although with relatively larger dimensions, as shown in Fig.3 [2].

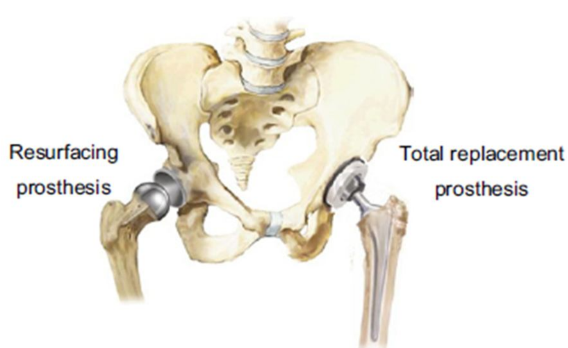

Fig.3: Total replacement and hip resurfacing hip prosthesis [2]

The main elements of the hip prosthesis are shown in Fig.4. In the total hip replacement (THR) there are a femoral stem, sunk into the medullar canal of the femur, a femoral neck, connecting the stem to the head and an acetabular cup that is embedded in the pelvis, in some cases through a backing insert (Fig. 4a). In resurfacing hip replacement (HRR) only the bearing couple, i.e. the acetabular cup and the femoral head, remains (Fig. 4b) [2].

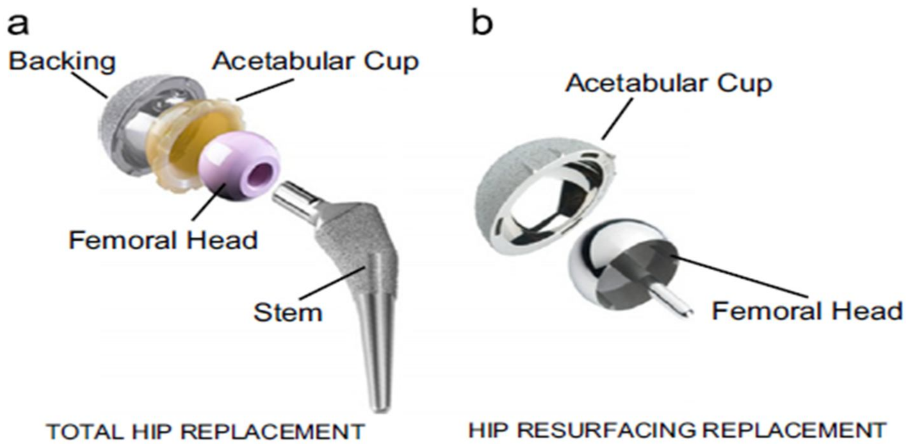

Fig.4: Main Components of an artificial hip joint [2]

B. Hip Replacement Implants

Hip replacements are among the most common orthopedic procedures. When a hip replacement is performed, the arthritic, damaged hip joint is removed. The ball-and-socket hip joint is then replaced with an artificial implant. The materials used in the implant depend on several factors, including the age of the patient, the activity level of the patient, and the surgeon's preference. Below are brief descriptions of some of the most commonly used hip replacement implants. It mainly consist of two types Hard-on- Hard and Hard-on-Soft implants. [17]

1) Hard-on-Hard Implants

a) Metal-on Metal Implants: Metal-on-metal (MOM) hip joint bearings are gaining more and more acceptance as an alternative to conventional metal-on-polyethylene (MOP) bearings. Some criteria in favor of MOM bearings are the excellent wear resistance, the influence of wear particles on the surrounding tissue, as well as the frictional torque. Recent developments of MOM bearings indicate a three times less frictional torque during simulated gait than MOP bearings. This is an interesting finding, because high friction was one of the reasons that the MOM prostheses lost their popularity at the end of the 1960s, after being quite fashionable for more than one decade. The idea of an all-metal joint was taken up again in the mid 1980s and led to the development of the so-called second generation metal articulation with improved alloy microstructure, surface finish and manufacturing tolerances. The families of cobalt–chromium–molybdenum alloys, which are suitable for self-bearing applications, include both cast and wrought materials with either low or high carbon contents. Typically, the carbon content is about 0.2% for the high carbon and below 0.08% for low carbon alloys. Carbon is responsible for the generation of carbides, which strengthen the material and affect the wear resistance [8]. Metal-on-metal (MOM) hip replacements avoid the problem of polyethylene wear debris induced osteolysis and have been extensively researched and developed in the past decade [6].

b) Ceramic on Ceramic Implants: Ceramics are good alternative to metal as bearing couple materials because of their better wear resistance. Ceramic has commonly been used for the femoral head in THR; however, it has not often been used in hip resurfacing. Therefore, an investigation of the possibility of using ceramic materials for resurfacing prostheses is meaningful. Although there are some concerns about the design limitations and the fracture of brittle ceramic implants, new alumina composites (alumina matrix composite and hot isostatic pressed alumina) provide better design facilities because of increased fracture toughness and bending strength [4]. Ceramic-on-Ceramic is a good combination with longevity and reliability. In these hip joints, the traditional metal ball and polyethylene liner are replaced by a high-strength ceramic bearing that has the reputation for ultra low wear performance. Ceramic-on-ceramic implants are designed to be the most resistant to wear of all available hip replacement implants. They wear even less than the metal-on-metal implants. Ceramics are more scratch resistant and smoother than any of these other implant material. [16]

Fig 5: Metal-on-Metal [9]

Fig 6: Ceramic -on-Ceramic [9]

2) Hard-on-Soft Implants:

a) Metal-on-Plastic Implants: The metal and plastic implants are the most commonly used hip replacement implants. Both the ball and the socket of the hip joint are replaced with a metal prosthesis, and a plastic spacer is placed in between. The metals used include titanium, stainless steel, and cobalt chrome. The plastic is called polyethylene. The implant is secured to the bone by one of two methods; it is either press-fit or cemented into place. In the press-fit method, the implant is fit snuggly into the bone, and new bone forms around the implant to secure it in position. [17]

Fig 7: Metal-on-Plastic Implants [9]

b) Ceramic on Plastic Implants: Ceramic-on-UHMWPE (Ultra High Molecular Weight Polyethylene) is a good combination of two very reliable materials. Ceramic heads are harder than metal and are the most scratch-resistant implant material. The hard, ultra-smooth surface can greatly reduce the wear rate on the polyethylene bearing. The potential wear rate for this type of implant is less than Metal-on-Polyethylene. Ceramic-on-Polyethylene is more expensive than Metal-on-Polyethylene, but less than Ceramic-on-Ceramic. [16]

C. Hip Replacement Implant Materials

All materials employed are biocompatible. In THR the femoral stem and neck are generally in stainless steel, cobalt-based alloy or titanium-based alloy, while the backing can be made from metal or plastics depending on its function. The metallic one is used with a plastic cup, in order to guarantee its fixation to the pelvic bone, whereas the plastic backing is used with metal or ceramic cup, for absorbing dynamic loads. Properties to consider when evaluating materials for bearings in THR include corrosion, resistance, strength, ductility, hardness, and frictional characteristics. The most common choice for the bearing surfaces, classified on the basis of material type, i.e. plastic (P), metal (M) and ceramic (C), are the following [2]: Head: M: stainless steel, CoCr and CoCrMo alloy; C: alumina and zirconia; Cup: P: UHMWPE, M: CoCr and CoCrMo alloy, C: alumina .The mechanical properties (elastic modulus E and Poisson's ratio) of the above mentioned materials and typical roughness values Ra are reported in Table 1. In addition, only in few cases titanium based alloys (e.g.Ti6Al4V) are used as material for the acetabular cup or the femoral head

Table 1: Mechanical properties of materials and typical roughness values for hip implant cup and head: Young's modulus E, Poisson's ratio ν, average roughness Ra [2]

Material		E(Gpa)	Poisson's ratio	Ra (um)
P	UHMWPE	1	0.4	0.1-2.5
M	Stainless Steel	210	0.3	0.01-0.05
	CoCrMo	230		
C	Alumina	380	0.3	0.01
	Zirconia	210		

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ISSN: 2321-9653
International Journal for Research in Applied Science & Engineering Technology (IJRASET)

D. Functional Anatomy of Hip Joint

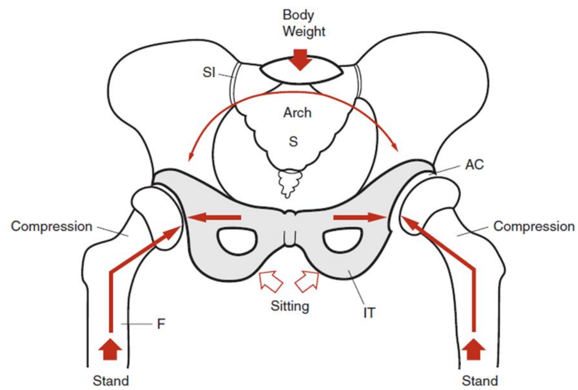

Fig 8: Functional anatomy of hip [11]

The human hip joint is well constructed for its intended use: standing and walking. The hip joint is an outstanding example of a congruous joint. Both the concave (acetabulum) and the convex (femoral head) are symmetrical, and the joint space is equal at all points with slight deviation to permit adequate lubrication. This symmetry allows for rotation about a fixed axis and simplifies the muscle action on that joint. The weight of the body is superimposed on the fifth lumbar vertebra and then transferred to the base of the sacrum(s) and across the sacroiliac joints (SI) to the ilia. When a person is standing, the weight of the body is transferred to the acetabula (AC) and finally to the femora (F). When a person is sitting, the weight is borne on both ischial tuberosities (IT).The femoral head articulates within the acetabulum, which is horse shoe shaped and coated with cartilage around most of its periphery. The center is free of cartilage. The bottom of the “ring” of the peripheral acetabulum is not complete. It is completed as a ring by the transverse acetabular ligament. The head of the femur fits into the acetabulum, where it is held firmly by a thick capsule, which is divided into thickened layers. In the standing position, the center of gravity passes behind the center of rotation of the hip joint. The pelvis is angled so that the femoral head is seated directly into the acetabulum. The head of the femur is coated by a cartilage that acts to cushion compressive forces and lubricates the joint during compression. When not bearing weight, the cartilage imbibes nutritional fluid. [11]

1) *Angle of Inclination:* The head and neck of the femur, when viewed from the front, are at an angle of inclination. Angle formed by intersecting femoral neck angle (NA) with axis drawn through shaft of femur (SA), which is termed angle of inclination. This angle normally varies between 90 degrees and 160 degrees, with an average of 135 degrees.[11]

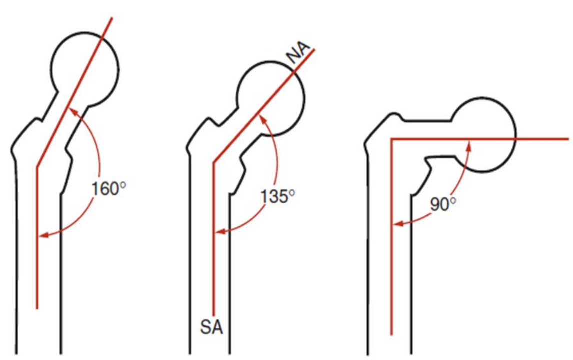

Fig 9: Angle of inclination [11]

E. Hip Range of Motion

Each Joint Has a Normal Range of Motion. Generally speaking, range of motion refers to the distance and direction a joint can move to its full potential. Each specific joint has a normal range of motion that is expressed in degrees after being measured with a goniometer (i.e., an instrument that measures angles from axis of the joint). Limited range of motion refers to a joint that has a

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reduction in its ability to move. The reduced motion may be a mechanical problem with the specific joint or it may be caused by diseases such as osteoarthritis, rheumatoid arthritis, or other types of arthritis. Pain, swelling, and stiffness associated with arthritis can limit the range of motion of a particular joint and impair function and the ability to perform usual daily activities. The hip joint has the following normal ranges of movement: Flexion, Extension, Adduction, Abduction, Medial Rotation and Lateral Rotation. [18].

1) *Flexion:* Bending movement that decreases the angle between two parts is termed as Flexion. Bending the elbow, or clenching a hand into a fist, are examples of flexion. When sitting down, the knees are flexed. Flexion of the hip or shoulder moves the limb forward (towards the anterior side of the body). Flexion of the hip is moving the thigh or top of the pelvis forward or brining the leg forward to the front as shown in fig 10.

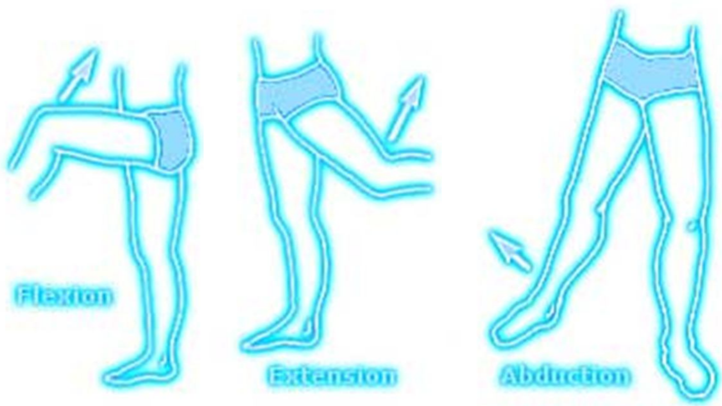

Fig 10: Flexion, Extension and Abduction [13]

2) *Extension:* It is the opposite of flexion a straightening movement that increases the angle between body parts. In a conventional handshake, the fingers are fully extended. When standing up, the knees are extended. Extension of the hip or shoulder moves the limb backward (towards the posterior side of the body). Hip extension is straightening the joint resulting in an increase of angle; moving the thigh or top of the pelvis backward or moving the leg to the backward as shown in fig 10.
3) *Abduction:* A motion that pulls a structure or part away from the midline of the body (or, in the case of fingers and toes, spreading the digits apart, away from the centerline of the hand or foot). Abduction of the wrist is called radial deviation. Raising the arms laterally is an example of abduction .Abduction of hip is moving the thigh outward with hip straight or moving the leg straight out to the slide as shown in fig 10

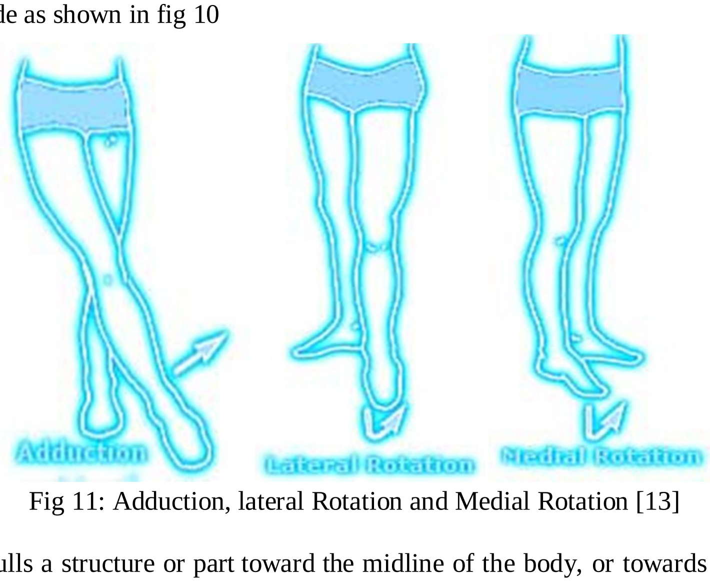

Fig 11: Adduction, lateral Rotation and Medial Rotation [13]

4) *Adduction:* A motion that pulls a structure or part toward the midline of the body, or towards the midline of a limb. Dropping the arms to the sides, or bringing the knees together, are examples of adduction. In the case of the fingers or toes, adduction is closing the digits together. Adduction of the wrist is called ulnar deviation .Adduction in hip is moving the thigh or leg inward with hip straight as shown in fig 11.

5) *Medial Rotation:* Internal rotation (or medial rotation) of the shoulder or hip would point the toes or the flexed forearm inwards (towards the midline).It is the rotary movement around the longitudinal axis of the bone toward the center of the body; turning the thigh or pelvis inward as shown in the fig 11.
6) *Lateral Rotation (External):* External rotation (or lateral rotation) is the opposite of internal rotation. It would turn the toes or the flexed forearm outwards (away from the midline).It is the rotary movement around the longitudinal axis of the bone away from the center of the body; turning the thigh or pelvis outward as shown in fig 11.

IV. WEAR OF HIP JOINT PROSTHESIS

Artificial joint replacements are effective in providing normal function to many patients suffering from severe joint diseases. The joint replacement treatment has been continuously evolved, from hips and knees to other major synovial joints. However, the joint bearings are subject to wear. Wear debris generated mainly from the joint bearing surface accumulates in local tissues, causes adverse tissue reaction, and ultimately leads to implant fixation failure. Wear induced failure remains a major limiting factor affecting the long term performance of the joint replacements, particularly for younger and more active patients. Recognition of the wear issue has led to extensive wear studies to predict wear performance, understand wear mechanism and evaluate design factors. Wear studies of artificial hip joint bearings have been largely carried out experimentally. Wear tests based on a simple bearing configuration using pin-on-plate testers are useful for identifying wear properties [7].

A. Wear of Implants

The two main critical issues for implant success are: 1) The implant fixation/loosening related to the implant/bone interaction.2) The wear of the articulating surfaces (femoral head and cup surfaces). The adverse tissue reactions to wear debris causes loosening and implants failure therefore the importance of biotribology in the development of long term artificial hip joints comes rather straightforward. The crucial issue for the bearing surfaces is the head–cup material couple, which is strictly related to wear [2]. Conventionally, hard-on-soft bearing couples such as metal- on-UHMWPE (ultrahigh molecular weight polyethylene) and ceramic-on-UHMWPE were widely used in THR. However, the wear debris released from the soft UHMWPE degrades the life of the hip implants [1]. Almost since the beginnings, around the1960s, the most used combination is metal-on-plastic (MoP), with a cobalt–chromium alloy head paired with a plastic cup. MoP and ceramic-on-plastic also denoted as soft on hard couples, are known to suffer from wear of the plastic part whose debris generate an adverse tissue reaction. In order to reduce the wear rate, alternative hard-on-hard material combinations have been prompted, both as metal-on-metal (MoM), used also for HRR, and ceramic-on-ceramic (CoC). However also these combinations have drawbacks: in MoM implants the main problem is related to the presence of potentially cancerous metal ions, developed from wear particles; on the other side the ceramics are brittle, therefore require particular care during intervention, and have also some manufacturing downsides that made them the most expensive solution [2]. The wear of the bearing surfaces of hip joint prostheses is a key problem causing their primary failure. As an important performance index of hip joint prostheses, wear progression of the bearing surfaces must be understood accurately. Previously both clinical and laboratory studies attempted to measure the wear of the implants to assess their performance. It has been shown that contact stresses in the bearing surfaces is critical to the progress of wear and hence affecting significantly the life of hip prostheses. In daily routine activities, a hip joint undergoes three-dimensional (3D) motions and gait loads and its bearing surfaces always experience varying contact stresses. Such repeated operation with time causes wear and damage of the bearing surfaces, and as a result, leads to osteolysis and aseptic loosening [1].

B. Contact Stresses & Contact Pressure:

In heavily loaded point or line contact such as gears, cams, rolling contact bearings, etc, the high load and low contact area results in high contact pressure. This contact pressure is known as Hertz contact stress or Hertz contact pressure. This high contact pressure leads to elastic deformation of surfaces in contact. Nowadays, hip joint arthroplasty is a common operation performed on patients varying from teenagers to elders. One of the most important problems that need addressing is hip implant wear. The distribution of contact pressure in the natural and artificial human joints is an important factor which affects the function of the joint. The contact pressure distribution on the hip prosthesis bearing surface is of special interest because it evinces the regions with high stresses. Exceeding the tolerance level of normal cartilage function, the subchondral bone and synovial membrane may cause degenerative changes, leading to osteoarthritis. [3]

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ISSN: 2321-9653

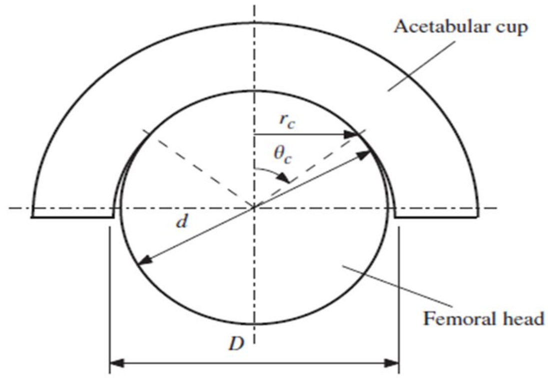

Fig 12: Contact between the two components. [3]

The total hip joint prosthesis is considered as being composed of a rigid sphere with diameter d and an elastic spherical cavity (socket) of diameter D as shown in fig 12. The head diameter d is considered to remain constant during the entire prosthesis life. Diameter D is considered to be constant during each gait cycle but variable from cycle to cycle. If no load is applied between the two elements and D is greater than d, the contact occurs only at a point as shown in fig 13(a). If one element is pressed with a force F, the two centers approach with a certain distance h, and the contact is spread on a spherical region of angle θ_c and radius r_c as shown in figure 13(b). [3]

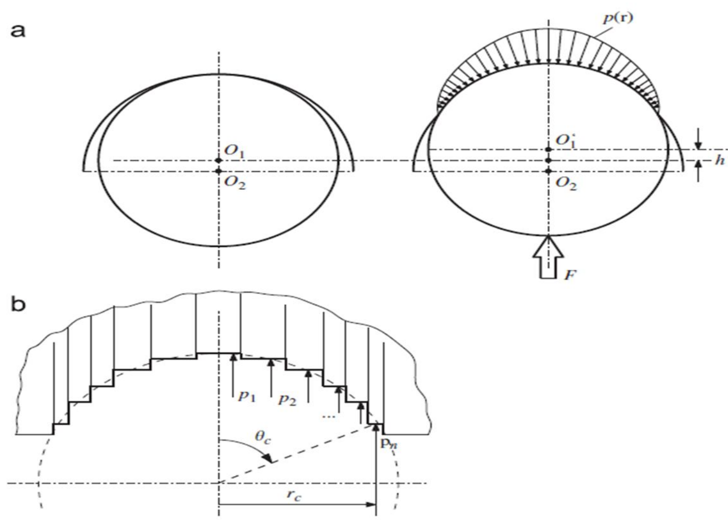

Fig 13: The contact pressure between the femoral head and acetabular cup [3]

C. Gait Cycle

Gait is the medical term to describe human locomotion, or the way that we walk. Interestingly, every individual has a unique gait pattern. It is the result of a series of rhythmic alternating movement of the legs (arms, and trunk) which creates forward movement of the body. The complete cycle start from the time of one foot touch the ground to the time the same foot touch the ground again. It is generally divided into stance (ST) and swing phases (SW) with ST usually representing 60% and SW 40% of the gait cycle in normal walking. Fig 14 shows the two phases of gait cycles. In figure 14 curved arrows depict flexion-extension of hip during normal gait. Hip initially swings 60 degrees of swing phase until heel strike (HS), when hip begins extension until heel off (HO) and toe off (TO). CG indicates center of gravity.

Volume 4 Issue II, February 2016
ISSN: 2321-9653

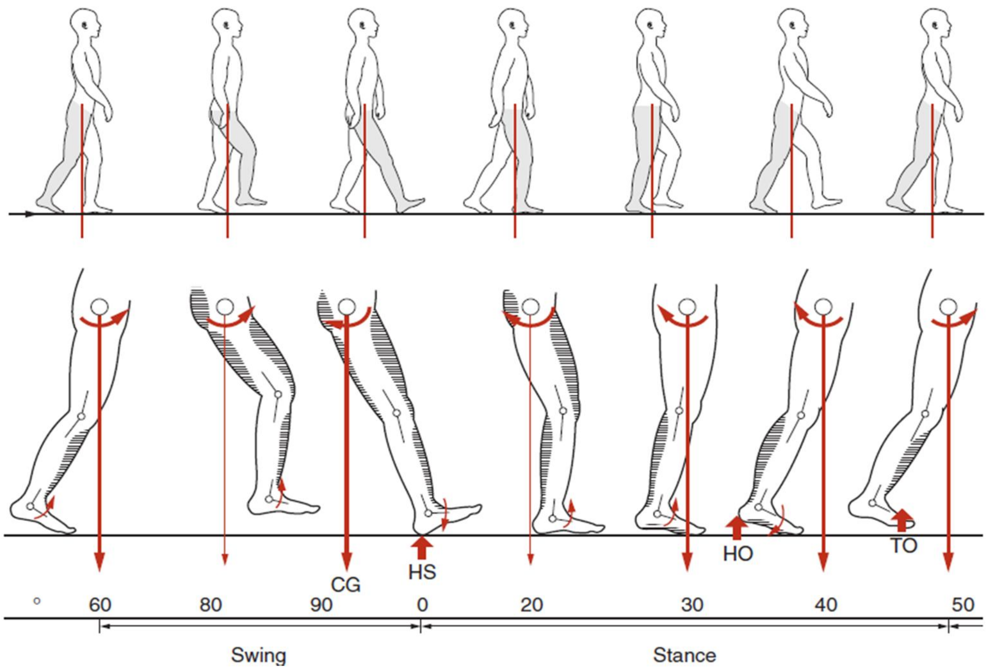

Fig 14: Gait cycle. [11]

1) *Stance phase:* The stance phase begins with the instantaneous event of initial contact (Heel strike) and continues as long as some portion of the foot is in contact with the ground and ends when the reference foot lifts off the ground (toe off).Stance phase is divided into 5 sub-phases: 1. Initial contact. 2. Loading response3. Mid-stance. 4. Terminal stance. 5. Pre-swing
2) *Swing phase:* Swing phase is called as the non weight bearing phase. The swing phase begins as soon as the big toe of one limb leaves the ground (after toe off), and finishes just prior to heel strike or contact of the same limb. It is divided into three sub phases: 1. Initial swing (acceleration) 2. Mid-swing 3. Terminal swing (deceleration).

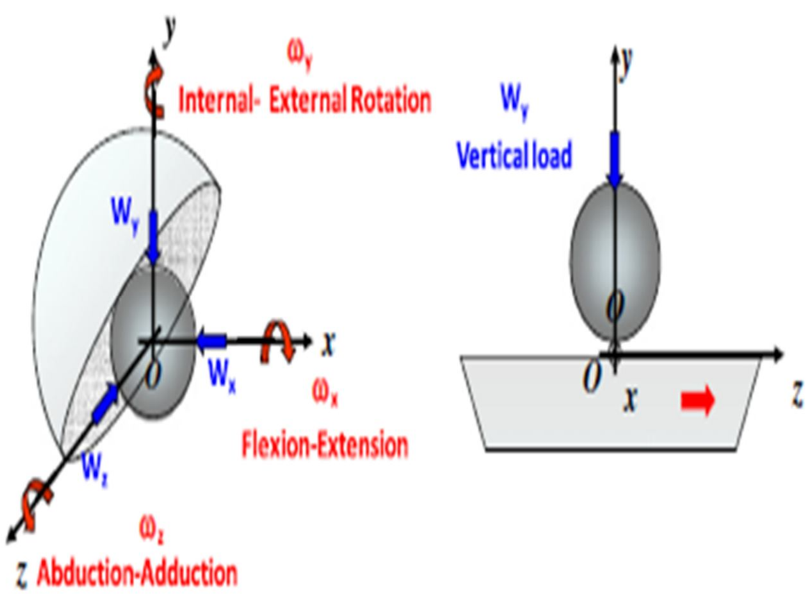

Fig 15: Model of the hip implant subjected, respectively, to the realistic 3D load and motion conditions and simplified conditions [2]

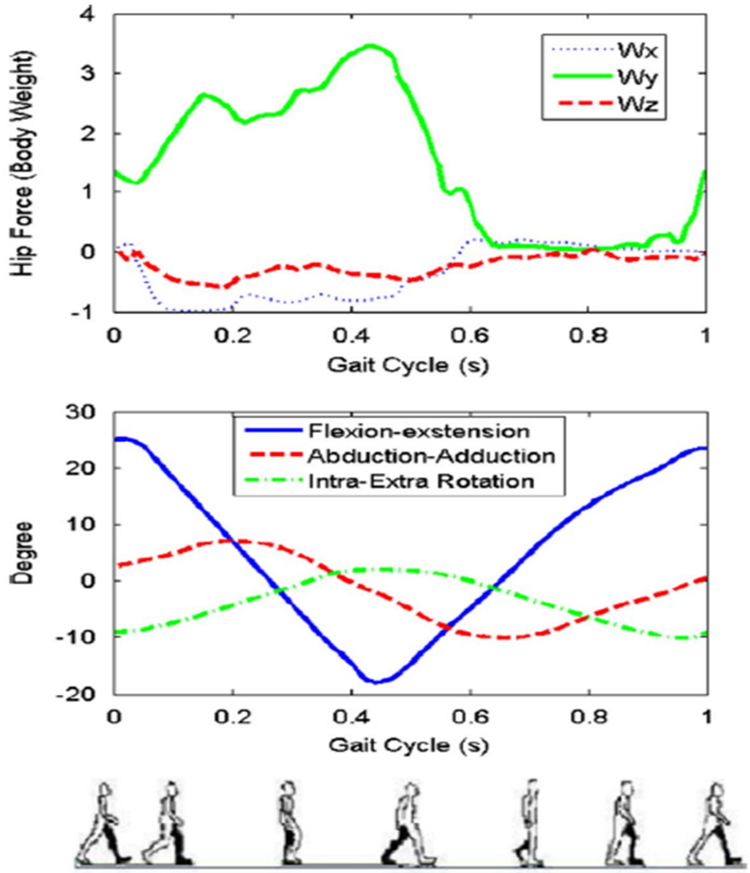

Fig 16: Hip force components and hip angles for normal walking during a gait cycle. [2]

Like the natural joint, hip implants in-vivo must be able to work under transient and wide range 3D physiological operating conditions, therefore triaxial load and angular velocity should be considered. The most complete database for loading conditions is due to Bergman et al. [5], who measured hip forces in nine daily activities, e.g. slow/normal/fast walking, walking upstairs/ downstairs, standing up/sitting down a chair, etc. While many authors reported hip contact forces, kinematic data as hip angles variation and angular velocities are not easily available. As standard daily activity for assessing performance after THA, reference is usually made to the normal walking gait cycle. An example of operating conditions for normal walking is reported in Fig. 16, showing the three components of the hip force, scaled with respect to the body weight (BW), and the corresponding hip angles, taken from ISO standard 14242-1. [2]

D. Wear Models Main Characteristics

Hip implant wear is recognized as the main cause of hip implant failure therefore has been widely investigated both experimentally and clinically, demonstrating the coexistence of abrasive, adhesive, fatigue and corrosive wear. Unfortunately experimental tests are often complex and expensive, in particular for hard-on-hard bearings and moreover experimental and clinical analyses can provide only short term information. Moving from these considerations, in the last few years several numerical wear models have been developed in order to predict long-term hip implant performance, in function of the design and manufacture parameters. [2] Wear models of hip implant are typically 3D and reproduce the realistic ball-in-socket geometry. The bearing surfaces of the femoral head and cup are highly conforming and usually modeled with a ball-in-socket geometry, characterized by the head and cup radii, R1 and R2, respectively, giving a radial clearance c=R2–R1 as shown in fig 17. In some papers, a ball-on-plane equivalent configuration is adopted, simply defined by the effective radius R and elastic modulus E.

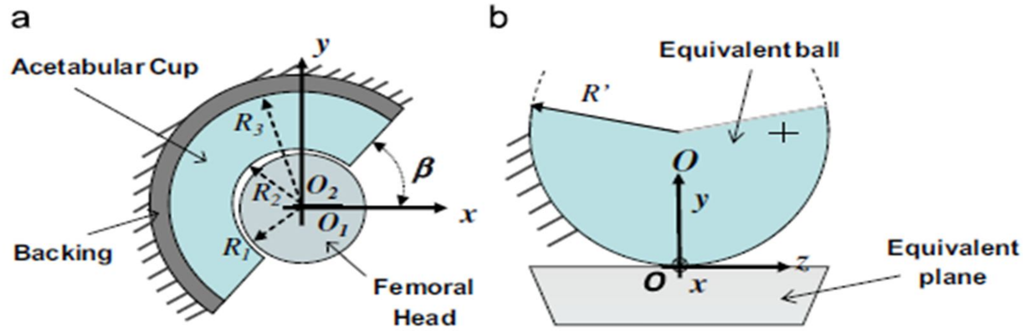

Fig17: Ball-in-socket (a) and ball-on-plane geometry (b) configurations for hip implants, where y is the vertical direction [2]

A distinction is made, depending on the material couple of the cup-head system, between rigid-to-flexible and flexible-to-flexible models. The former are used for soft-on-hard implants where the plastic acetabular cup, backed with a metal insert, is considered to be in contact with the rigid surface of the femoral head. On the other side, flexible to flexible wear models are generally used for hard-on-hard implants, where both the acetabular cup and femoral head must be described as3D deformable bodies. [2] Wear models aim at predicting wear trends caused by 3D physiological working conditions in long term life service. Usually normal walking is the simulated daily activity; load and motion can be described as 3D components or, more often, as simplified condition, considering only flexion–extension movements. The operating conditions are applied as boundary conditions to the models. In the rigid-to-flexible cases, load and motion act on the rigid surface of the femoral head, while the cup is fixed. For flexible-to-flexible models, constraints and loads can be applied to the head or to the cup. [2]

E. Governing Equations and Numerical Approach

Wear models of artificial hip joints describe the dry contact between articular surfaces, completely neglecting lubrication. Most numerical models describe wear revolution in time by implementing Archard's wear law or Reye's hypothesis in commercial FE codes as ABAQUS and ANSYS by means of specific user-defined routines Archard's law is commonly adopted for its simplicity and validity in wide applications, even if it can describe only adhesive and abrasive wear mechanisms. As well known, it linearly relates the volumetric wear with the resultant normal load and the relative surface sliding distance. [1]

$$U_v = kW_nS \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where, U_v = Volumetric wear, W_n = Resultant normal load, S = Relative surface sliding distance and k = Dimensional wear coefficient, sometimes also denoted as wear factor, dependent on the coupled materials and their wettability, on surface finishing and on lubrication. In wear models, Eq.1 is usually implemented in terms of linear, instead of volumetric wear also denoted as wear depth.[1]

$$U_L = k\sigma S \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where, U_L = Linear wear, σ = Normal contact stress on the contact area

In the above equation both stress s and displacement s are point-dependent and are evaluated at each node of the contact surface. Moreover, the wear process is also temporally simulated, therefore the transient operating conditions are sampled in n steps and the linear wear is evaluated as the cumulative effect of each step.[1]

$$U_L = \sum U_L = \sum k_i\sigma_iS_i \ldots\ldots\ldots\ldots\ldots (3)$$

Where the contact stress σ_i and the sliding distance S_i of the considered node are calculated by the FE code at each the time- step i. Summing up, the hip wear model takes prosthesis geometry, physiological load and motion as inputs, evaluates pressure distribution and sliding distance for each worn element node, hence, assuming a certain wear coefficient, returns 3D wear distribution. Clearly the problem is strongly time dependent and requires a progressive up-date of the surface geometry caused by wear damages. It is worth noting the relevant role of the wear coefficient in the reliability of the wear model firstly, it accounts for a vast array of different factors such as material combination and properties, surface roughness ,friction coefficient, lubrication regime and temperature; secondly any error in its estimation is linearly transferred to the model.

V. CONCLUSION

Tribological behavior of hip implants is the key issue for improving the reliability of these elements, wear being one of the main causes of their limited service life. The wear analysis of hip joint prosthesis has been analyzed in this study by using three-dimensional motions, gait loads and finite element model and the effect of varying contact stress and pressure distribution on bearing surface of hip implants. Wear model is used to investigate the effect of geometric and material parameters on the wear trends in physiological conditions. Due to the gait motion, the intensity and location of the maximum contact stress in the bearing components change with the gait instances. With a given geometry and gait loading, the linear and volumetric wear on the cup surface increases with the number of the gait cycle's .With the increase of gait cycles, the contact pressure distribution will be scattered due to the effect of the localized wear on the surface. In this case study detailed study of comprehensive finite element analysis of the contact stress and wears in hard on hard hip joint prosthesis under 3D physiological gait loading in walking cycles has been carried out. Compared to ceramic-on-ceramic and metal-on-metal, PCD- on-PCD bearing couple has the lowest wear progression in terms of cumulative linear and volumetric wear. As wear progresses the contact between the cup and the head changes continuously. Until now constant wear coefficient value is used for the bearing couples for simulation. Hence different values of wear coefficients can be used for simulation in future work. The current wear model was based on the abrasion-adhesion wear. To more accurately estimate the wear of hard-on-hard implants, other wear mechanisms, such as those due to surface fatigue and tribocorrosion need to be incorporated in future. The hip loading adopted is based on the steady state gait cycles, but in-vivo abnormal gait loading from wide range of activities may intensify stresses which may result in an increased wear. The current wear simulation is limited up to 2×10^6 cycles (equivalent to 2 years of implant) which may not be sufficient to reflect actual wear evolution. As is widely reported, generally THRs in human body are expected to survive 15–20years or more. It is thus important to study and evaluate wear progression for a longer period of time, which will enable us to predict more realistic behavior of contact and wear of THRs.

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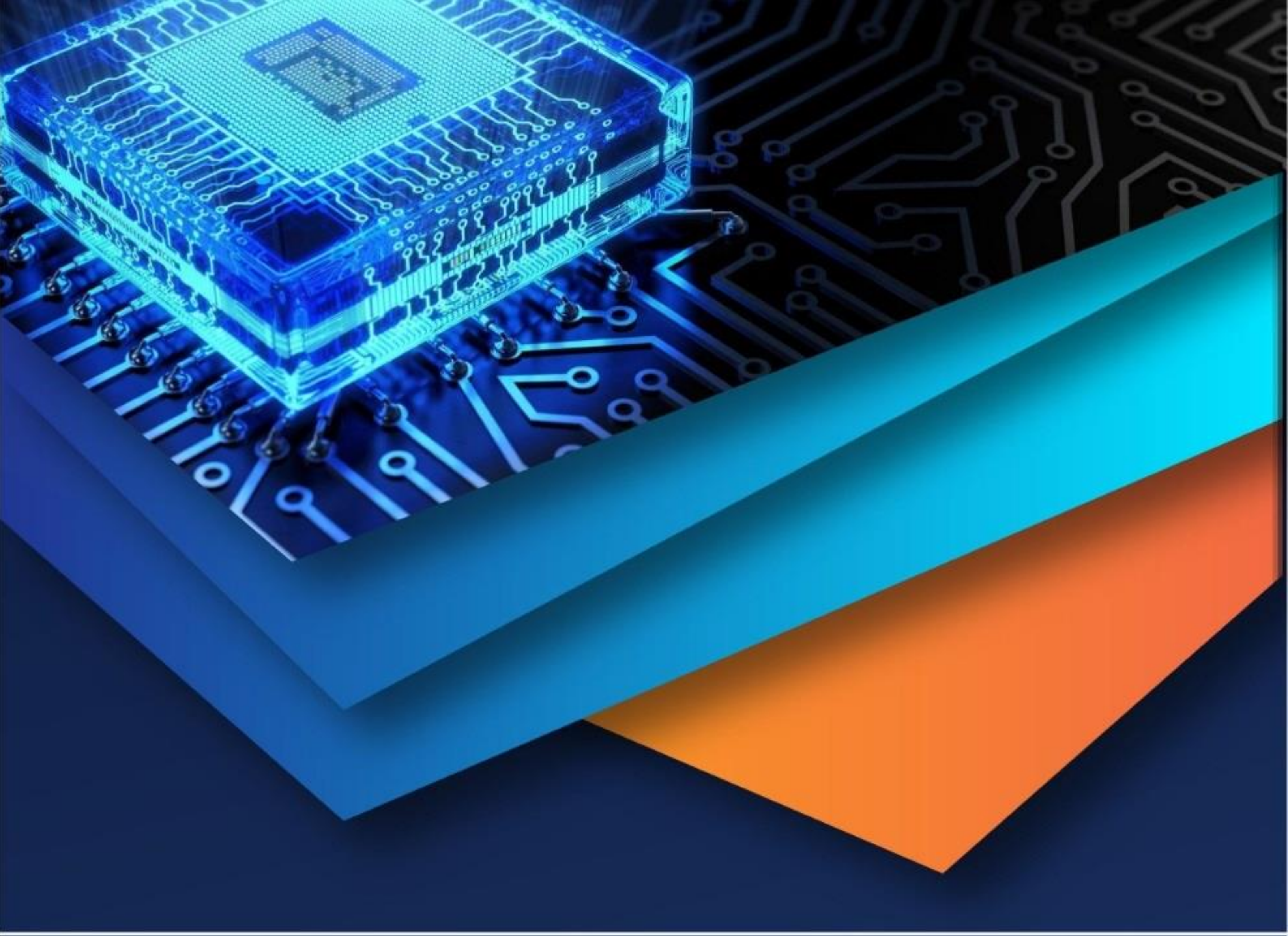

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