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Analysis of various human synovial joint replacements: A review

[1] Sugandha, [2] Dr. Puneet Katyal, [3] Dr. Munish Gupta.
[1] P.G. Student, Mechanical Engineering Department, Guru Jambheshwar University of Science & Technology, Hisar (India)-125001,
[2][3] 3Assistant Professor, Mechanical Engineering Department, Guru Jambheshwar University of Science & Technology, Hisar (India)-125001

Abstract: **-- Human body has six types of synovial joints throughout. These joints can be damaged by arthritis and other diseases, injuries, or other causes. Replacing a damaged joint or a paining joint can relieve pain and help one move and feel better. For fabrication of prosthesis, study and analysis of human synovial joints is required. Hips and knees are replaced most often. Other joints that can be replaced include the shoulders, fingers, ankles, and elbows. To better understand the behaviour of replacement joints, various studies have been conducted and formulations have been done on similar systems. In this review paper an attempt has been made to understand the basics of synovial joint, and various studies and analysis done on implants using mathematical and simulator methods.**

Keywords- **elastohydrodynamic lubrication (EHL), synovial joint**

I. INTRODUCTION

Adult human body has 206 bones and the points where these bones meet are called synovial joints. Synovial joints are most evolved and therefore most mobile type of joints. Synovial joints vary in structure from place to place, but they can be classified in 6 general types.

1.Gliding joint (move against each other on a single plane. e.g. wrists and ankles)

2.Hinge joint (move on only one axis e.g. elbow and finger joints)

3.Pivot joint (provides rotation e.g. at the top of the spine, the atlas and axis form a pivot joint that allows for rotation of the head)

4.Condyloid joint (circular motion, flexion, and extension e.g. wrist joint between the radius and the carpal bones)

5.Saddle joint (allows flexion, extension, and other movements, but no rotation. e.g. the hand, the thumb's saddle joint lets the thumb cross over the palm)

6.Ball-and-socket joint (freely moving joint rotatable on any axis. e.g. hip and shoulder joints)

Any of these joints in human body is essentially a synovial joint with same synovial fluid acting as a lubricant. Synovial joints are characterized by the presence of an articular capsule between the two joined bones. Articular capsule is fibrous in nature and is lined by synovial membrane Bone surfaces at synovial joints are protected by a coating of articular cartilage. The articular surfaces are supported and reinforced with cartilage. This articular cartilage is avascular, non- nervous and elastic. This limits movement to prevent injury. Because of its rich nerve supply the fibrous capsule is sensitive to stretches imposed by movements. The anatomy of a joint is shown in fig.1.

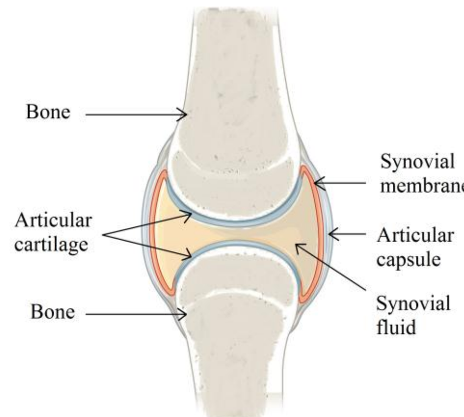

Fig.1 Anatomy of a human joint

The prosthetic limbs and joints used for the replacements are made based on the studies of natural limb movements. Modeling for a joint is done based on the motion and properties desired by that limb. The lubrication within the human joint is done by synovial fluid. The lubrication properties of this synovial fluid have been studied over the years using concepts of elastohydrodynamic lubrication.

Elastohydrodynamic lubrication (EHL) is the type of hydrodynamic lubrication where the contact pressure is so high that the interacting surfaces deform elastically by an amount comparable to the film thickness. Therefore, in elastohydrodynamic lubrication, elastic deformation of the surfaces and pressure dependence of viscosity both play a fundamental role in the generation of load carrying film which is thick enough to separate the surfaces completely.

Two common forms of EHL contacts are encountered in engineering applications viz. point contact and line contact.

- Point Contact: If a sphere or an ellipsoid comes in contact with a flat surface, a point contact is formed. Examples of point contact are ball bearings and pin on disc configurations.

- Line Contact: If a cylinder comes in contact with a flat surface, a line contact is formed. Examples of line contact are the rolling element bearings, mating gear teeth, cam and followers and synovial joints etc.

The analysis of Elastohydrodynamic lubrication in load bearing human joints is a more speculative example because the understanding of various aspects of the tribological behavior of synovial joints is incomplete. In recent years, total joint replacements for osteoarthritis joints have received considerable attention as an effective alternative. However, these artificial joints suffer from almost unavoidable complications due to loosening, instability and wear of articulating components. This has inspired several researchers to develop new and improved implant designs over the last few decades. The focus of experimental and theoretical research investigations pertaining to biomechanics has shifted to long-term effectiveness and survival of total joint replacements.

II.LITERATURE ON HUMAN JOINTS

Total joint replacement (TJR) also known as total joint arthroplasty (TJA) is regarded among the most valued developments in the history of orthopedics. Over 200,000 total hip replacements (THRs) and 350,000 total knee replacements (TKRs) are carried out annually in the United States. Fundamental to replacing damaged joint surfaces with implants fabricated from materials, is the requirement of producing a low friction bearing to minimize surface wear, inflammation in surrounding tissues and possible eventual loosening of the implant, resulting in the need for revision surgery. Theoretical investigations, being convenient and economical, play a major role to serve the aforesaid purpose. Likewise, many studies have been done on synovial joints. Hips and knees are replaced most often. Some studies are joint specific while others deal with overall nature of the synovial fluid. Few of them are reviewed here.

Ahmad and Singh [1] considered the lubrication synovial fluid as a stokes couple-stress fluid and found inverse relationship between couple stress parameters and load capacity. They registered sharp fall in load capacity on increase of fluid film thickness more than 0.1, the model was found reasonable above $\tau > 20$.

Kumaresan et al. [2] compared four non-linear models namely slideline, contact surface, hyperelastic, and fluid model for study of cervical spine facet synovial joint subjected to compression, flexion, extension, and lateral bending. The results were found to be most accurate in fluid model. Sideline model and contact surface model gave least accurate results.

Ateshian et al. [3] constructed a three-dimensional geometric model of the articular surfaces of the thumb carpometacarpal joint with least squares surface fitting technique for males and females using single parametric biquintic spline function. The data was collected from above 55 years people through stereophotogrammetry. No gender-related differences were found to exist regarding the shape of the metacarpal surface, while female trapezium was found significantly smaller than that of the metacarpal. Overall, female joints were found to be less congruent than male joints.

Giurintano et al. [4] modelled thumb as five virtual links connected by hinge joints. Homogeneous matrix transformations were used to move the bones and the tendon control points from their resting posture. Although the complexity of equation was more compared to three link rigid models, the five link model was suggested to be used as base of information for carpometacarpal prosthesis.

Kovler et al. [5] constructed three-dimensional (3-D) computer models of the articular surfaces of CMC joints of older humans and determined their locus of cartilage degeneration. A common articular wear pattern observed was significant degeneration in the dorsoradial quadrant of the trapezium.

Jalali-Vahid et al. [6] have conducted study on metal-on-metal hip implant using the effective influence Newton (EIN) method. The EHL model is considered having isoviscous conditions and regarded as "soft EHL". With the convergence of 10-4, the minimum film thickness along the centre-line in the entraining direction was noted to be 25% higher under in-vivo and 50% higher under in-vitro condition than the overall minimum film thinkness.

Wang et al. [7] proposed a general numerical methodology to analyse EHL on compliant layered socket against a rigid ball under steady state rotation for flexion and extension in hip joints during walking. Reynold's equation and full elasticity equation were solved using Newton-Rapson method, finite element method, and fast Fourier transform technique. Use of fast Fourier transform technique in combination with finite element method was found to provide accurate predictions in 20 times reduced computation time.

Unsworth[8] discussed various reasons of failures of joint replacements and suggested the use of more advanced tribological design for low wear rates and extended life of prosthesis. He also discussed theoretical approaches of the artificial hip joint. Comparision of many combination of joints with bovine serum lubrication was was discussed and Ceramic-on-ceramic joints, compliant layer joints, and large diameter metal-on-metal joints were concluded to be better options for future researches.

Neville et al. [9] discussed scopes of biomimicry of synovial joint lubrication. Two separate layers hyaluronate and proteinaceous with astonishing property were resulted from centrifugation of synovial fluid. Potential benefits from biomimicry of synovial fluid in reduction in friction coefficient in various places were identified and proposed.

Dowson and Jin [10] discuss the reintroduction of metal on metal hip replacement in prostheses on its working in boundary layer regimes over the fluid film regime functioning of the polyethylene material. Also in boundary lubrication regime, boundary lubrication concepts alone determines friction and wear and when fluid film lubrication prevails, physical hydrodynamic considerations will control joint behaviour. They concluded that metal on metal joints have strength, durability and low wear rates than metal/ceramic-on-polyethylene joint.

Gao et al. [11] employed multi-level multi-integration and fast fourier transform in spherical model for hip joints numerical solution considering EHL. However MLMI and FFT individually gave errors, the combined MLMI–FFT method was found to provide with a numerical accuracy with relative errors at the order of magnitude of 10-5 in the deformation, compared to the MLMI method.

Dowson [12] has discussed total replacement of hip joints materials types, metal-on-polymer, ceramic-on-polymer, metal-on-metal, ceramic-on-ceramic, ceramic-on-metal, metal-on-ceramic cushion bearings. New bearing configurations such as metal-on-metal, ceramic-on-ceramic, ceramic-on-metal and cushion joints offer great reductions in wear and penetration of the femoral head into the acetabular cups.

Jalali-Vahid et al. [13] investigated the effect of start-up and gait initiation upon elastohydrodynamic lubrication (EHL) in a typical metal-on-metal hip implant using a ball on plane model. Investigation suggested that intermittent motions associated with start-up and stop doesn't have much effect on wear of metal-on-metal hip implants.

Wismans et al. [14] presented a three-dimensional analytical model of the knee-joint with geometry of joint surfaces and material properties of ligaments and capsule. Surface geometry was approximated by polynomials in space derived from a large no of points on the joint surfaces. The model successfully represented many aspects of mechanical behaviour of the knee- joint, but did not show variations with change in stiffness of ligaments and capsule.

Blankevoort et al. [15] considered and analysed rigid contact mathematical description, and deformable contact description based on a simplified theory for contact of a thin elastic layer on a rigid foundation, for knee joint model. Simulation of the passive motion characteristics of the knee, the simplified description for contact of a thin linear elastic layer on a rigid foundation was concluded to be a valid approach when aiming at the study of the motion characteristics for moderate loading conditions.

Hefzy and Yanget al. [16] constructed a three-dimensional mathematical model based on two-point contact was assumed between the femur and patella at the medial and lateral sides. Rotation matrix was employed to express the system of coordinated and constraintsfrom model were used. Through the model it was seen that that as the angle of knee flexion increased, the lateral contact point moved distally on the femur without moving significantly either medially or laterally.

Bendjaballah et al. [17] considered a three dimensional non-linear finite element model of the knee joint. Computer-assisted tomography with direct digitization and measurements were employed to reconstruct the detailed geometry of joint. The results indicated that the maximum principal stresses are oriented approximately normal to the contact surfaces and are almost completely in compression except for small regions on the cartilage edges that undergo negligible tension.

Gill and O'Connor [18] developed a biarticulating two-dimensional model of the patellofemoral joint using geometric and force equilibrium constraints. Iterative numerical procedure was followed to calculate flexion angle angle and reaction force magnitude. The model demonstrated the gross kinematics and mechanics of the patellofemoral joint in the sagittal plane.

Blankevoort and Huiskes [19] compared and validated the three-dimensional mathematical models of the tibio-femoral joint with the kinematics of four knee joint specimens. Quasi static model for knee based on equilibrium of forces and moments was considered. The model was successfully validated for passive motion characteristics of the human knee joint.

Kennedy et al. [20] conducted a study on different materials for artificial knee joints in oscilating conditions simulation for total knee replacement. Through the numerical analysis of EHL in the oscillatory line contact between the ultrahigh molecular weight polyethylene (UHMWPE) and cobalt-chrome alloy (CoCr) and wear model methodology, it was realized that with lubrication greatest wear is shown near the ends of the wear track, where the oscillating specimens have zero velocities, change their direction of motion. Without lubrication peak was found near the center of the wear track, with no increase in wear at the ends of the wear track.

Mongkolwongrojn et al. [21] presented the transient analysis of artificial knee joint under EHL point contact with non-Newtonian lubricants simulated under load and velocity conditions during walking. Time dependent Reynolds's equation and elasticity equation were simultaneously solved using perturbation method, Newton Raphson method and multigrid method with full approximation. It was concluded that minimum film thickness reaches a quite low value during that first walk cycle and the response of the fluid film reaches steady state in the second walk cycle which is maintained in subsequent walk cycles.

Procter and Paul [22] considered ankle as two joints, the talocalcaneonavicular and the talocrural for a three dimensional analysis. Ankle was treated as two rigid free body segments and a force and momentum analysis was done. The analysis gave acceptable results for stance phase without inclusion of ligament constraints.

Wynarsky and Greenwald [23] developed and analysed simplified mathematical model for pressure distributions in both the anterior-posterior and medial-lateral directions and contact area growth plots. The joint was considered as circular half cylinder and simple trigonometric relation were used for analysis. The generated pressure profiles showed that peak stresses occur at the two initial points of contact while the central regions are minimally stressed, esp. for light loads.

Dul and Johnson [24] investigated spatial gross motion of the foot with respect to the shank as rotations about two fixed ankle axes: the upper ankle rotation axis (plantarflexion/dorsiflexion) and the subtalar rotation axis (inversion/eversion). Location and orientation of foot were noted in coordinate system and 4×4 transformation matrix was used for modeling. The model was found usable for posture and motion simulations.

Leardini et al. [25] formulated a two-dimensional four-bar linkage model of the ankle joint, to describe dorsi/plantarflexion in unloaded conditions. From experiments, the human ankle joint complex was deduced to behave as a single-degree-of-freedom system during passive motion, with mobility is allowed by the sliding of the articular surfaces upon each other.

Hlavacek [26] presented a squeeze-film lubrication model of the human ankle joint with synovial fluid filtrated by articular cartilage. Joint was taken as cylindrical with synovial fluid as a mixture of viscous Newtonian hyaluronic acid-protien phase and ideal phase of low molecular weight substances. He used partial differential equations, and MATLAB for calculations and observed the model for fluid transport near the articular surface that is important for synovial fluid filtration and occurs early after the step-load application.

Bandak et al. [27] developed a three-dimensional finite element model of the human ankle joint to study the impact injury in kinematic conditions. The simulated model was evaluated for the same. The model was concluded to have reasonable overall mass and stiffness characteristics and is capable of reproducing the experimental input/output responses for a range of impact velocities below 4.47m/s of impact.

Bruening et al. [28] suggested an anatomically based correction for more accurate ankle joint center. Lower extremity radiographs were experimentally generated. They suggested to define a simple correction factor, which would be subsequently evaluated by its effect on six degree-of-freedom ankle joint translations during normal gait.

Ruggiero et al. [29] proposed an approximate closed form lubrication model of the human ankle joint considering porosity of the cartilage matrix and the non-Newtonian behaviour of the synovial fluid. They modified Reynolds equation to obtain a couple-stress fluid model for synovial fluid. Modified Darcy's equation was employed for synovial fluid transport across the articular cartilage. Non-Newtonian nature of the synovial fluid was taken into account by stokes micro-continuum theory. The model was concluded as useful for all dynamic analyses of the ankle joints.

III. SUMMARY

Prosthesis is a very fast advancing and wide field. Many theories and formulation of laws have been done regarding the law conducting synovial fluid. Various models assume the synovial fluid differently like elastohydrodynamic lubrication, stokes couple stress fluid. Many mathematical approaches like Newton-Rapson Method, Gauss-Seidal iterative method, finite element method, fast Fourier Transform Technique, multi level multi integration have been applied to try to achieve a universal governing formulation for the synovial joints. There is still a great debate about the definite mechanism(s) of lubrication in synovial joints. There is high scope of improved different and more efficient formulation leading to cheap prosthesis with increased work life are the future perspectives in this field.

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