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Synovial Joints and Lubrication mechanisms

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Synovial joints form the most important feature of the human body as they represent the centers of the most essential and basic activity in the human beings, which is motion. A synovial joint can be described as a load carrying system consisting of two mating bones with tangential and /or normal motions. The bone ends, which are usually spherical in appearance, are covered with a soft sponge like material, called articular cartilage. The space between these cartilaginous extremities of the bones, known as joint cavity, is filled with a shear- dependent fluid called synovial fluid. The surfaces of the synovial joints have a high degree of geometrical conformity.

The behaviour of a synovial joint is mainly governed by the characteristics of the articular cartilage and synovial fluid. The articular cartilage is a soft glistening tissue with thickness varying between 1 to 7 cm, with young's modulus between 10^6 and 10^8 dynes/cm^2 , with permeability of the order $4.3x10^{-13}$ cm^4 dyne^{-1} sec^{-1}, and the pore diameters of the order $6x10^{-7}$ cm. Its surface is rough and varies with a regular periodicity of 20-50 micro metre and amplitude of 2 to 5 micro metre.

The synovial fluid is a clear yellowish dialysate of blood plasma with a concentration of hyaluronic acid molecules of about 3.5 mg/gm. The hyaluronic acid is a straight, long chain polymer compound with molecular weight 500000 and molecular length of the order of $5x10^{-3}$-10^{-4} cm. Acid molecules do not normally pass through cartilage pores because of the smaller size of these pores.

The synovial fluid exhibits a non Newtonian pseudo plastic behavior. Its viscosity depends also on the concentration of the hyaluronic acid molecules. When bones approach one another, water and other low molecular weight molecules pass through the pores of the cartilage and the hyaluronic acid molecules stay behind, thus increasing the concentration of these molecules in the synovial fluid increasing its viscosity.

Geometrically knee joint is regarded as separated by cylindrical surfaces but the hip joint as separated by spherical surfaces. The radii of these surfaces vary from 2 to 100 cm. The sliding speed of the joint varies from 0 to 10 cm/sec. The load support area is larger for a hip joint than for a knee joint. The structure of the knee joint is such that it can support a load four times the body weight.

In a diseased joint, the cartilage surface can become rough and cracked and synovial fluid can lose its non- Newtonian behavior. The pores of a cartilage may increase in size and the hyaluronic acid molecules may be able to pass through them. One object of mathematical modeling of joints is to enable us to know the each of these factors in the performance of the joints. It investigates the lubrication systems that are operative in synovial joint. Depending on the loading conditions and sliding velocity during one gate of the walking cycle the profile of the synovial film thickness and the pressure developed.

Lubrication depends on light irregularities in the joint surface that trap hyaluronate, Lubricin molecules to create a fluid film over the cartilage surface, elastic deformation of the cartilage to maintain a layer of fluid between opposing cartilage surfaces, alternate application and removal of compressive forces to create fluid flow and fluid being squeezed out of cartilage into the joint space as loading increases.

LUBRICATION MECHANISMS-

1. Boundary Lubrication- Boundary lubrication arises when the separation of bearing surfaces is of molecular dimension 10^{-7}-10^{-6} cm. It occurs when each load bearing surface is coated with a thin layer of large molecules that forms a gel that keeps the opposing surfaces from touching each other. The layers slide over each other more readily than they are sheared off the underlying surface. In human diarthrodial joints, these layers contain the lubricin that adheres to the articular surface. This type of lubrication is considered to be most effective at low loads. The load capacity is determined by the molecular properties of lubricants and roughness of surfaces, but the viscosity of the fluid does not play an important role.

2. Fluid- Film Lubrication- Fluid film lubrication involves a thin fluid film that provides separation of joint surfaces. Surface lubricated by a fluid film typically have a lower coefficient of friction than do boundary lubricated surfaces and the fact that the coefficient of friction is very low in synovial joints suggests that some sort of fluid film lubrication exists. Several models or fluid film lubrication exist including hydrodynamic, hydrostatic, weeping lubrication, squeeze film lubrications, elastohydrodynamic (a combination of hydrodynamic and squeeze film) and boosted lubrication.

Hydrodynamic lubrication- Hydrodynamic lubrication is a form of fluid lubrication in which a wedge of fluid is created when non parallel opposing surfaces slide on each other. In hydrodynamic lubrication, the thickness of the fluid film is between 10^{-4} and 10^{-3} cm [1]. This is much larger than the surface roughness thickness. Hydrodynamic lubrication is generally characterized by conformal surfaces [2].The pressure in the fluid film is generated because of relative motion of surfaces and wedge action. The viscosity of the fluid, the geometry and relative motion of the surfaces may be used to generate sufficient pressure to prevent solid contact [3].The resulting lifting pressure generated in the wedge of fluid and by the fluid's viscosity keeps the joint surface apart. The magnitude of the pressure developed is not generally large enough to cause significant elastic deformation of the surfaces. The minimum film thickness in a hydrodynamically lubricated bearing is a function of normal applied load, surface velocity, lubricant viscosity and geometry [2]. If the surfaces are not moving and the pressure is generated by external pumping, the term hydrostatic lubrication is used.

Weeping lubrication- Weeping lubrication is a form of fluid lubrication in which the load bearing surfaces are held apart by a film of lubricant that is maintained under pressure. . In engineering, the pressure is usually supplied by an external pump. In the human body, the pump action can be supplied by contractions of muscles around the joint or by compression from weight bearing compression of articular cartilage causes the cartilage to deform and to "weep" fluid which forms a fluid film over the articular surfaces. The fluid can only move into the joint, because the impervious layer of calcified cartilage keeps it from being forced into the subchondral bone. When the load is removed the fluid flows back into the articular cartilage through osmotic pressure. Weeping lubrication represents a special form of self-acting hydrostatic bearing mechanism, which has been advanced by McCutchen (1967) [4]. He believes that when cartilage is pressed against an opposing surface it wrings fluid from its structure to the interface and in this way provides a film of fluid on which the joint rides. The concept of weeping lubrication is based on the assumption that cartilage is a weeping bearing and load is carried by the hydrostatic pressure of the fluid when cartilage weeps under loading, even though the liquid content of the porous cartilage would be expelled and there would be an increase in the friction coefficient if the squeeze is maintained indefinitely. It also appears that the wringing out of water from the porous matrix follows a longer and difficult path while resoaking is easy. This type of lubrication is most effective under conditions of high loading but it works under most conditions. The process is essentially the building up of pressure in the fluid within the porous elastic cartilage by the application of load to the surface of the cartilage. The effect is produced and governed by the resistance to flow in a direction perpendicular to the load and the elastic properties of the cartilage [5]. Fluid flow onto the cartilage surface probably occurs at the periphery of the area of impending contact where the pressure is lower rather than at the center of the contact area where the pressure is highest. Weeping lubrication term was used because bearing materials, which do it, weep liquid when compressed [4].

Squeeze –Film lubrication – Squeeze-film lubrication occurs when the bearing surfaces are moving perpendicularly towards each other. Pressure is created in the fluid film by the movement of articular surfaces that are perpendicular to one another. As the opposing surfaces move close together, they squeeze the fluid film out of the area of impending contact. The viscosity of the fluid in the gap between the surfaces produces pressure, which tends to force the lubricant out. The resulting pressure created by the fluid’s viscosity keeps the surface separated. This type of lubrication is suitable for high loads maintained for a short duration. This mechanism is capable of carrying high loads for short lengths of time. As the fluid is forced out, so the layer of fluid lubricant becomes thinner and the joint surfaces come into contact. The height of the film can be measured under certain circumstances, and a squeeze-film time determined as the time taken for the film to diminish under load from a given height to zero.

Elastohydrodynamic lubrication- In the elastohydrodynamic lubrication model the protection fluid film is maintained at an appropriate thickness by the elastic deformation of the articular surfaces. Elastohydrodynamic lubrication is a hydrodynamic process in which fluid film pressure causes elastic deformation of the bearing surfaces which in turn modify the pressure in the film region. In other words, the elastic cartilage deforms slightly to maintain an adequate layer of fluid between the opposing joint surfaces. The elastohydrodynamic action can maintain a fluid film under conditions of heavy loading. The fluid film thickness is in the range 10^{-5} to 10^{-4} cm. In general, the elastic distortion provides a greater geometrical conformity than normally exists in the contact region, and this, in turn, provides a much thicker lubricating film for a given load. Furthermore, this high pressure may cause a substantial increase in lubricant viscosity. This viscosity effect further increases the thickness of the lubricating film [6]. The minimum film thickness is a function of the same parameters as in hydrodynamic lubrication with the addition of the effective elastic modulus [2].

Boosted Lubrication- The boosted lubrication models suggests that pools of concentrated hyaluronate molecules are filtered out of the synovial fluid and are trapped in the natural undulations and areas of elastic deformation on the articular surfaces. The concept of boosted lubrication is base on the assumption that nominal contact areas are formed due to roughness waves of the cartilages when the cartilage surfaces are pressed against each other. The synovial fluid is trapped in these nominal areas and there is a hogh concentration of hyaluronic acid molecules in the trapped fluid because water and other low molecular weight substances have diffused into the cartilage. This higher concentration leads to a great load bearing capacity[7].

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