The 1st Regional Conference of Eng. Sci. NUCEJ Spatial ISSUE vol.11, No.3, 2008 pp 522-535

The Role of Lubrication Mechanisms in the Knee Synovial Joints

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Abstract:

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. Starting from the role that are played by the lubrication regimes in effectiveness and maintenance of the joint this study was initiated. 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 in the knee joint when the hydrodynamic and elastohydrodynamic lubrication regimes are operative was determined.

For the hydrodynamic and elastohydrodynamic lubrication analysis a mathematical model obtained by solving the governing equation using numerical methods. Results showed that for the hydrodynamic action the minimum film thickness determined was between (0.365-1.8) µm and the pressure developed ranged between (20.6-860.449) kN/m^2. While for elastohydrodynamic action the minimum film thickness ranged from (2.5-3.57) µm and the developed pressure ranged between (97.68-146.5) kN/m^2. Finally, it was shown that in specific conditions hydrodynamic and elastohydrodynamic lubrication mechanisms gave a good explanation to how the joint functions.

Keywords: hydrodynamic, elastohydrodynamic, joint lubrication, knee joint

Introduction:

Despite being subjected to very varied and sometimes very high loads, the articular surfaces in synovial joints of the human body undergo minimal wear. This is due to the lubrication processes occurring within the joints. To understand these processes, the basic engineering principles of lubrication should be considered.

There are two basic mechanisms of lubrication in engineering: -

1.Boundary lubrication mechanism.
2.Fluid-film lubrication mechanism.

Each mechanism complements the other and depends on the tissues involved and the load imparted to the joint [1,2].

Surfaces that contact each other during joint motion and give rise to frictional resistance have been defined as:

1. Cartilage-on-Cartilage type

The mechanisms of cartilage-on-cartilage lubrication have been attributed to the boundary lubrication effects and the presence of fluid-film lubrication.

1.1. Boundary lubrication

The term boundary lubrication refers to the situation where a lubricant film is present between two rubbing surfaces but its thickness is insufficient to prevent asperity contact through the film [3]. The boundary effect of synovial fluid in a cartilage-on-cartilage system is that the synovial fluid readily adheres to the cartilage surfaces, helping to keep them apart and decreasing frictional forces. The contact lubrication mechanism is governed by glycoprotein fraction of synovial fluid, which sticks firmly to the articular cartilage surfaces [2]. The thickness of the surface film varies from (1 to 10) nm depending on the molecular size. The frictional characteristics are determined by the properties of the solids and the lubricant film at the common interfaces [4]. It was shown that the fat in the surface layer of articular cartilage was important, since removing it chemically without apparent damage to other structures increases the coefficient of friction [5]. Boundary lubrication of articular cartilage is extremely effective in preventing wear due to motion but loses its protective abilities under high loads [2]. Therefore, other lubricating mechanisms must be at work.

1.2. Fluid-film lubrication

An important geometrical feature of fluid-film contacts is that the films are many times thicker than the height of the irregularities on the surfaces of the solids [6].

Load on the bearing surfaces in fluid-film lubrication is supported by the pressure in the film. The excellence of the lubrication system in this tissue is reflected from the value of the coefficient of friction, where its value is 0.002 compared with 0.03 for ice on ice lubricated by water and 0.2 for steel on steel lubricated by oil [7].

1.2.1 Hydrodynamic lubrication

Hydrodynamic lubrication is generally characterized by conformal surfaces [4]. If the bearing is of convergent shape in the direction of motion, the fluid adhering to the moving surface will be dragged into the narrowing clearance space, thus building-up a pressure sufficient to carry the load. This is the principle of hydrodynamic lubrication [3].

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 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 [4]. Most lubricating films operating under hydrodynamic conditions have a thickness of the order of $(10^{-4}$ -$10^{-3})$ cm [6].

1.2.2 Elastohydrodynamic lubrication

Elastohydrodynamic lubrication (EHL) is defined as hydrodynamic lubrication in which the fluid-film pressure causes elastic deformation of the bearing solids, which in turn influences the development of pressure within the film. 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 [7].

In human joints the viscosity of synovial fluid varies negligibly with pressure over the pressure range encountered in synovial joint [4,5,8,9,10] where the modulus of elasticity of the articular cartilage are very small, the articular cartilage deforms readily under physiological loads, and the lubrication regime can, thus, be regarded as isoviscous-elastic. The most significant feature of elastohydrodynamic action is that the minimum film thickness becomes almost insensitive to load. The film thickness is almost constant over most of the effective contact zone, with a restriction providing the minimum separation near the outlet end .It should be noted that the term 'contact' is used to describe a region of load transmission between lubricated solids; it does not necessarily imply that the solid touch. An increase in load flattens out the elastic solid and increases the size of the contact zone without having much effect upon the minimum thickness of the 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 [4].

1.2.3 Squeeze-film lubrication

Squeeze-film lubrication occurs when the bearing surfaces are moving perpendicularly towards each other. The viscosity of the fluid in the gap between the surfaces produces pressure, which tends to force the lubricant out. 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. The mechanism of squeeze film lubrication can be summarized as follows: as the load is applied to the undulating surface of the cartilage layers, the synovial fluid separating the surfaces becomes pressurized. This pressure forces the lower molecular weight constituents from between the surfaces and possibly into the pores of cartilage, and the remaining fluid becomes rich in hyaluronate, which increases the viscosity of the fluid. When the surfaces become very close the trapped pools of enriched fluid help to support the load and allow easy sliding of one surface relative to the other. As the load is reduced the lower molecular weight elements are sucked into the joint interface by the hydrodynamic action, thereby recharging the joint for the next load cycle. The loading of cartilage against a flat sheet of glass with synovial fluid between provided a glimpse of the trapped pools when examined on the scanning electron microscope. These trapped pools appeared to consist of mucine, highly concentrated into the depressions on the surface of the cartilage with two or three layers in the deep depressions [5].

1.2.4 Weeping lubrication

Weeping lubrication represents a special form of self-acting hydrostatic bearing mechanism, which has been advanced by McCutchen (1967) [8]. 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. This wept fluid is composed mainly of water and small ions. Pore size in articular cartilage has been measured to be approximately 60 nm. This small pore diameter restricts the passage of large molecules such as the mucopolysaccharide of the cartilage matrix and hyaluronate and synovial fluid protein while allowing passage of interstitial fluid of the cartilage [2]. 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 [6]. 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. Fluid flow out of the cartilage toward the subchondral area is blocked by subchondral plate, and sideways flow is retarded by the relatively poor perfusion characteristics of cartilage [2]. Weeping lubrication term was used because bearing materials, which do it, weep liquid when compressed [8].

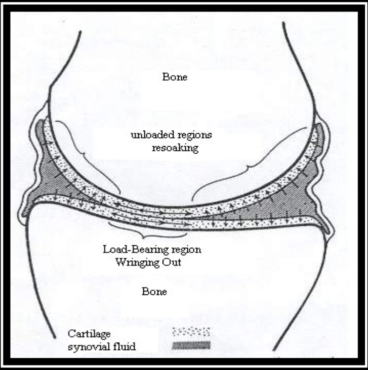

Figure -1: A Simplified Joint, Showing How Cartilage Remains Soaked in Service: Wringing Out Follows a Difficult Path While the Resoaking is Easy [8]

2. A soft tissue interface (Synovium-on-Synovium interface or Synovium-on-Cartilage)

Lubrication of synovial surfaces by synovial fluid requires hyaluronate due to boundary phenomenon.

2.1. Boundary lubrication

Boundary lubrication occurs when each bearing surface is coated or impregnated with a thin layer of lubricant that keeps the sliding surfaces apart, allowing ease of motion with a low coefficient of friction between the sliding surfaces. Hyaluronate sticks to the synovial surfaces .The lubricating properties of synovial fluid in a soft tissue system are directly related to the concentration and molecular weight of the hyaluronate, which is also determined by viscosity. However, it is not the viscosity of synovial fluid that is responsible for lubrication of this system but the sickness or boundary phenomena exhibited by the fluid. Viscous solutions containing no hyaluronate do not lubricate a soft tissue system nearly as well as containing no hyaluronate of equal or even lower viscosity [2].

Loads and Motions of Synovial Joints:

Human joints are specifically for transmitting large normal loads from one bone to another while allowing an efficient relative motion in a direction tangential to the surfaces. Loads vary considerably from joint to joint and from moment to moment and so it is intended to look at specific joint and activities to establish the pertinent features [8]. Load acting on joints of the lower limb during activity are rarely constant for very long. Figure (2) shows the variation in load and sliding velocity in the knee joint for a typical walking cycle. The maximum loads are about 1750 N and occur when the heel strikes the ground and the toe is leaving the ground. Just before “heel strike” and shortly after “toe off” the loads reduce rapidly toward zero. The sliding velocity in the knee also varies considerably with time in normal walking. This pattern is followed throughout the walking cycle, always when the load is high the sliding velocity is low and when the load is low the sliding velocity is high.

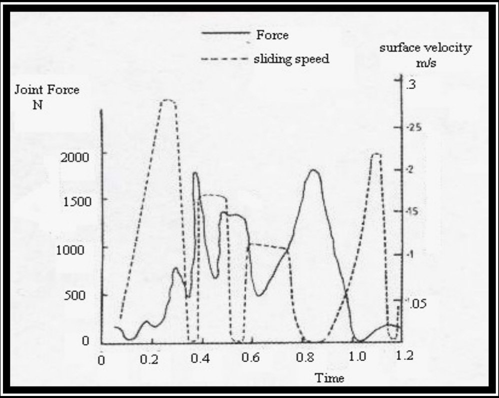

Figure -2: Knee Joint Forces and Surface Velocities at Different Parts of the Walking Cyc [8].

Regarding the ways that loads and surface velocities combine at various instances in the walking cycle, it seems possible to isolate specific sets of conditions for independent study. Two extremes of conditions immediately suggest themselves. Firstly, the lightly loaded portions of the cycle during which the surface velocities are high and the heavily loaded regions where the surface velocities approach zero [8]

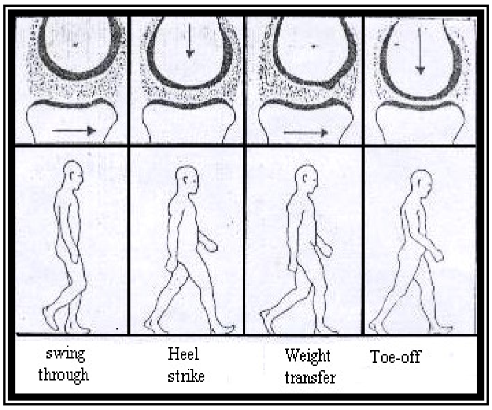

Figure -3: Lubrication Mechanism Illustrated for the Right Knee [8].

The important aspects of human joint lubrication are depicted in Figure (3). This shows a diagrammatic representation of the knee joint above its corresponding position in walking cycle. During the almost unloaded “swing phase”, includes a period where a very small load coincides with a high sliding velocity, when the foot has left the ground and the leg is swing freely from its posterior to its anterior position, a relatively thick film of synovial fluid can be entrained into the space between the cartilages. This has been shown to be able to generate full fluid film lubrication, specifically the hydrodynamic lubrication. When the heel strikes the ground, the load on the knee suddenly increases while the entraining velocity is reduced towards zero. Here, the thick film generated begins to squeeze out and the film thickness reduces. However, since the load is applied for only a short time in normal walking, the squeeze film mechanism is able to maintain a viable film of lubricant throughout this stage. As the cycle progresses, the load on the knee reduces and the entraining velocity increases. This is the phase in the walking cycle where theoretical and experimental results suggest elastohydrodynamic lubrication. In this way, the synovial fluid film separating the joint surfaces can be maintained. Finally at the “toe off” position, the load is maximum and the entrainment velocity is very low but again “squeeze-film” lubrication can maintain a fluid film and prevent surface-to-surface contact [1,5] and the probability of boundary lubrication share the squeeze film lubrication at this stage of walking cycle as a lubrication mechanism [5].

A Model of the Human Joint for Lubrication Studies:

It is convenient and permissible to represent certain synovial joints, like knee joint, by a cylinder near a plane configuration for the purpose of analysis; the plane solid is assumed to be rigid and the opposing component consists of a rigid core (representing the bone) covered by a layer of porous, elastic material (representing the articular cartilage). Synovial fluid was approximated as a Newtonian lubricant [6, 12,13,14,15].

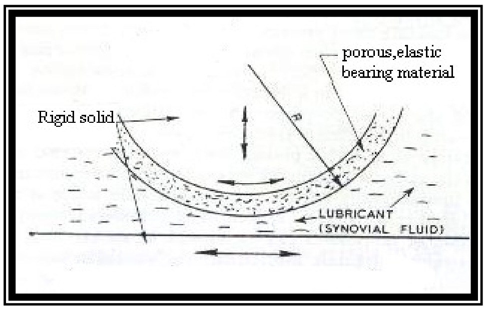

Figure – 4: Model of Equivalent Bearing [6].

Knowing the velocities of the surfaces and their geometry, we can calculate the pressures in the synovial film with Reynolds equation.

$$\frac{\partial}{\partial x}\left(\frac{\rho h^3}{12\eta}\frac{\partial p}{\partial x}\right)=\frac{\partial}{\partial x}\left(\frac{\rho(u_a+u_b)}{2}\frac{\partial h}{\partial x}\right)+\rho\left(w_a-w_b-u_a\frac{\partial h}{\partial x}\right)+h\frac{\partial \rho}{\partial t} \qquad 1$$

Hydrodynamic Term squeeze local Term

expansion

Where x and y are special coordinates along the direction of motion and in transverse direction, respectively; p=p(x) is the pressure in the contact; h=h(x) is a function describing the separation between two interacting bodies (film thickness), ρ is the density, η is the

viscosity ; u^a and u^b are surface velocities of the two articulating bones.
For hydrodynamic lubrication the motion is pure sliding, so that w is zero.
The following usual assumptions are considered:

- Newtonian fluid
- Iso-viscous fluid
- Incompressible fluid
- Steady state condition
- Isothermal condition
- Smooth surfaces
- Inertia effect neglected

We need to satisfy the following boundary conditions:

At the inlet p=0

At the outlet $p = \frac{\partial p}{\partial x} = 0$

The motion was assumed as pure sliding, ignoring the squeeze term, and by applying the last assumptions; equation (1) become

$$\frac{\partial}{\partial x}\left(\frac{h^3}{\eta}\frac{\partial p}{\partial x}\right) = 6U\frac{\partial h}{\partial x} \qquad 2$$

where $U = u_a + u_b$

This equation can be integrated with respect to x to give

$$\frac{1}{\eta}\frac{dp}{dx} = \frac{6U}{h^2} + \frac{A}{h^3} \qquad 3$$

Making use of boundary condition that

$\frac{dp}{dx}=0$ at

$x = x_o \quad , h = h_o$

$\therefore A = -6U\eta h_o$

Substituting this into equation (3) gives

$$\frac{dp}{dx} = 6U\eta\frac{h - h_o}{h^3}$$

$$\frac{dp}{dx} = 6U\eta\frac{h - h_o}{h^3} \qquad 4$$

This is the integrated form of Reynolds equation. The subscript (o) refers to the condition at all points where $dp/dx = 0$.

1. Hydrodynamic lubrication

To find out whether the hydrodynamic pressure is high enough to carry the contact load or not, and what fluid layer thickness is expected in the contact between the bearing surfaces. The classical hydrodynamic theory of lubrication for rigid cylindrical surfaces lubricated by an iso-viscous lubricant was adopted and solved by using Cameron's solutions [17,18].

Pressure distribution:

The classical Reynolds equation for hydrodynamic lubrication is used to find the pressure distribution in a bearing with an incompressible lubricant, for the geometry of figure (4)
Solving eq.(4) and by using boundary and initial conditions, the dimensionless pressure (p*) at any point can be found from

$$p^* = \frac{1}{2}\left[\gamma + \frac{\pi}{2} + \frac{\sin 2\gamma}{2} - 1.2257\left\{\frac{3}{4}\left(\gamma + \frac{\pi}{2}\right) + \frac{\sin 2\gamma}{2} + \frac{\sin 4\gamma}{16}\right\}\right] \qquad 5$$

Film thickness equation for rigid body:

Typical line contact of hydrodynamic solution for minimum film thickness (h_o) is Martin's solution [16], where formulas for rigid-isoviscous lubrication are applied to the case of hydrodynamic pressure.
For a cylinder-plane configuration, the film thickness at position x is: $= h_0 + \frac{x^2}{2R}$
Where h_o represents the minimum film thickness, which are derived in references [17, 18] as:

$$h_o = 4.9\frac{\eta U R}{W} \qquad 6$$

2. Elastohydrodynamic lubrication

The essential feature of this regime of lubrication is the elastic modulus of the bearing surfaces and the pressure-viscosity coefficient.
For the synovial joint this regime is denoted as soft (EHL) [4,7] because of its modulus of elasticity is very small. The viscosity of synovial fluid varies negligibly with pressure over the pressure range encountered in a synovial joint [8]. The articular cartilage deforms readily under physiological loads, and the lubrication regime can, thus, be regarded as isoviscous-elastic [4].

For this regime of lubrication, the pressure developed in the joint and thickness of the lubricant can be estimated in the next sections using a combination of direct-iteration and Newton Raphson techniques for solving the elastohydrodynamic lubrication system.

Pressure distribution

Equation (2) is first written in the following residual form

$$f=\frac{d}{dx}\left(\frac{\rho h^3}{\eta}\frac{dp}{dx}\right)-6u\frac{d(\rho h)}{dx}=0 \qquad (7)$$

Equation (7), solved in dimensionless form at each node i:

$$f_i=H_i^{\,3}\left(\frac{dP}{dX}\right)_i-K\overline{\eta}_i\left(H_i-\frac{\rho_o H_o}{\rho_i}\right) \qquad (8)$$

$$\rho=1+\frac{0.6*10^{-9}P_H*P_i}{1+1.7*10^{-9}P_H*P_i} \qquad (9)$$

Where

$$U=\frac{\eta_\circ u}{E'R}\quad K=\frac{3\pi^2 U}{4W^2}\quad W=\frac{w}{E'R}$$

$$X=\frac{x}{b}\qquad H=\frac{hR}{b^2}\qquad \overline{\eta}=\frac{\eta}{\eta_\circ}$$

P= p / P_H

$\overline{\eta}=1$

Isoviscous condition

as a result equation (8) can be written as

$$f_i=H_i^{\,3}\left(\frac{dP}{dX}\right)_i-K\left(H_i-\frac{\rho_o H_o}{\rho_i}\right) \qquad (10)$$

Film thickness

The film-thickness equation that considers body surface deformation is used. For line-contact problems we only need to add a proper film geometry term in the other direction and replace the displacement term in the film thickness equation by the elastic deformation.

The equation of elastic deformation that are adopted in this study are Okamura's approach [19], where he assumed simply that

$$\delta=-\frac{1}{2\pi}\sum_{j=1}^{N}P_j\ln\left(\left|\frac{X_{i+1}+X_i}{2}-X_j\right|\left|\frac{X_{i-1}+X_i}{2}-X_j\right|\right) \qquad (11)$$

Where δ describes the elastic deformation of the surfaces.

$$\therefore h=h_o+\frac{x^2}{2R}+\delta \qquad (12)$$

The present algorithm is based on both direct-iteration and Newton-Raphson techniques. Two main iteration loops are established in this algorithm. The inner loop, a Newton-Raphson scheme is used to update the pressure distribution with equation (8). The pressure corrections are obtained by using a tridiagonal pseudo-Jacobian matrix. In the outer iteration loop, the conventional direct method is used to adjust the central film thickness.

Finite difference form of the governing equation:

The method of finite differences is used to approximate the governing equations at discrete points; the contact region is divided into several sub regions, each of which is discretized with a uniform grid configuration.

Discretization form of the Reynolds equation

Equation (7) is first written in the following residual form:

$$f=\frac{d}{dx}\left(\rho H^3\frac{dp}{dx}\right)-12U\frac{d(\rho H)}{dx}=0 \qquad \mathbf{13}$$

...

The standard second order central difference formulas are used to approximate the residual function; Equation (13) is first expanded to read

$$f=\left[\left(3\rho H^2*\frac{dH}{dx}\right)+H^3\frac{d\rho}{dx}\right]\frac{dp}{dx}+\left[\rho H^3*\frac{d^2p}{dx^2}\right]-12U\frac{d(\rho H)}{dx} \qquad (14)$$

After discretization, the difference equivalence of equation (14) is then obtained

$$f_i^R=\left[\left(3\rho H^2\right)_i\frac{H_{i+1}-H_{i-1}}{2\Delta x}+H_i^{\,3}\frac{\rho_{i+1}-\rho_{i-1}}{2\Delta x}\right]\frac{p_{i+1}-p_{i-1}}{2\Delta x}+\left(\rho H^3\right)_i\frac{p_{i+1}-2p_i+p_{i-1}}{(\Delta x)^2}-12U\frac{(\rho H)_{i+1}-(\rho H)_{i-1}}{2\Delta x} \qquad (15)$$

Where the subscript "i" denotes a grid point, the grid spacing Δx, is constant in a sub-region in which uniform grids are used.
A mixed second-order central and first-order backward differencing scheme is used to approximate the function from which the Jacobian matrix is generated. Equation (13) is rewritten as

$$f = \frac{d}{dx}\left(\rho H^3\right)\frac{dp}{dx} + \rho H^3 \frac{d^2 p}{dx^2} - 12U\frac{d(\rho H)}{dx} \tag{16}$$

After discretization, equation (16) becomes

$$f_i^J = \frac{\left(\rho H^3\right)_i - \left(\rho H^3\right)_{i-1}}{\Delta x}\,\frac{p_{i+1} - p_{i-1}}{2\Delta x} + \frac{1}{2}\left[\left(\rho H^3\right)_{i+1} + \left(\rho H^3\right)_{i-1}\right]\frac{p_{i+1} - 2p_i + p_{i-1}}{(\Delta x)^2} - 12U\,\frac{(\rho H)_i - (\rho H)_{i-1}}{\Delta x} \tag{17}$$

The first-order forward-difference formula is used to evaluate $\partial f_i^J / \partial p_j$ which is denoted as (DFJ).

$$\begin{aligned} DFJ(i,j) = & \left(\left(\frac{\left(\bar{\rho}_{i+1} k_{i,j-1} H^3_{i+1} + 3H_{i+1}^{\ 2}\rho_{i+1} DH_{i+1,j}\right) - \left(\bar{\rho}_i k_{i,j} H_i^3 + 3\rho_i H_i^2 DH_{i,j}\right)}{2\Delta x}\right)\left(p_{i+1} - p_{i-1}\right)\right) \\ & \left(\left(\frac{\rho_{i+1} H_{i+1}^{\ 3} - \rho_i H_i^3}{(2\Delta x)^2}\right)\left(k_{i,j-1} - k_{i,j+1}\right)\right) + \\ & \left(\left(\frac{\left(\bar{\rho}_{i+1} k_{i,j-1} H^3_{i+1} + \rho_{i+1} 3H_{i+1}^{\ 2} DH_{i+1,j}\right) + \left(\bar{\rho}_i k_{i,j} H_i^3 + 3\rho_i H_i^3 DH_{i,j}\right)}{(2\Delta x)^2}\right)\left(p_{i+1} - 2p_i + p_{i-1}\right)\right) + \\ & \left(\left(\frac{\rho_{i+1} H_{i+1}^{\ 3} + \rho_i H_i^3}{\Delta x^2}\right)\left(k_{i,j-1} - 2k_{i,j} + k_{i,j+1}\right)\right) - \frac{AS_{i,j}}{\Delta x} \end{aligned} \tag{18}$$

where $\bar{\rho} = \dfrac{d\rho}{dp}$

$$AS_{i,j} = K * \left(\left(\bar{\rho}_i * k_{i,j} * H_i + \rho_i * DH_{i,j}\right) - \left(\bar{\rho}_{i-1} * k_{i,j+1} * H_{i-1} + \rho_{i-1} * DH_{i-1,j}\right)\right) \tag{19}$$

This set of equations along with the boundary conditions can be rearranged into the following matrix form.

$$\left[\frac{\partial f_i}{\partial p_j}\right]\left\{\Delta p_j\right\} = -\left\{f_i^R\right\} \tag{20}$$

where (Δp) is the correction to the pressure distribution in the course of an iteration.
A Gauss elimination method is used to solve this linear system.

Discretization form of the elasticity equation

Equation (11) can be discretized as follows:

$$\delta_i = -\frac{1}{2\pi}\left(\sum_{i=2\ j=2}^{NN} Log\left(\left|\frac{X_{i+1} + X_i}{2} - X_j\right|\left|\frac{X_{i-1} + X_i}{2} - X_j\right|\right) * P_j\right) \tag{21}$$

$$H_i = H_o + \frac{(X_i)^2}{2} - \delta_i \qquad \textbf{22}$$

Assessment of the Film Thickness During Different Phases of Walking Cycle:

A complete lubrication analysis during one walking cycle requires taking full account of the loading and cycle of movements in a natural synovial joint.

Solutions are generated for parameters, have been chosen for the steady sliding conditions, taken from the previous investigations [20] which are:

- Radius of equivalent cylinder near a plane R, 0.1 m.
- Absolute viscosity of synovial fluid η, $2*10^{-3}$ Pas.
- Eeffective elastic modulus E, 10^7 N/ m^2

The load and sliding velocity in the knee joint for a typical walking cycle was taken from the curve shown in figure (2) [5, 8], which is matched with the information presented in figure (3), to provide a brief description on the performance of the synovial joint, especially knee joint, during different phases of the walking cycle and detecting the maximum load applied on the joint during each phase of the cycle.

In the knee joint the period of one walking cycle is determined as 1.2 sec [5, 8]. Mainly this period is divided into two phases: swing phase and stance phase.

The swing phase lasts about 0.556 sec and includes a period where a very small load coincides with a high sliding velocity. From figure (3) it is shown that during the swing phase there is a sliding velocity of about 0.28 m/s, accompanied by a load ranging between 40 N to 750 N. under these conditions hydrodynamic lubrication mechanism operate to provide a thick film separate the two bony surfaces.

In this range of conditions all film thickness calculations tends towards that described by rigid cylinder and isoviscous lubricant theory [6, 20, 21], which gives:

$$h_o = 4.9\frac{\eta UR}{W}$$

The values of minimum film thickness (h_o) for the synovial fluid during the swing phase are presented in table (1).

In the stance phase, which lasts about 0.644 sec of the walking cycle, it includes two periods: one of the periods occurs when a very high loads, for about 1750 N, coincides with a very low sliding speed, at heel strike and toe off, at this period the squeeze film mechanism will operate which squeeze the lower molecular weight constituents from between the surfaces into the pores of the cartilage. Squeeze-film lubrication supports the knee joint for about 0.144 sec; i.e.12% of the walking cycle, whereas the squeeze-film lubrication supports the hip joint for about 50% [11]. This is because that the loads applied on the hip joint is greater than that applied on the knee joint as a result the squeeze-film lubrication occupies a major portion of lubrication for the hip joint during walking cycle. In a squeeze film analysis the compliant surface squeeze film situation may be approximated by considering a squeeze film between rigid surfaces having the same shape as the elastically deformed surfaces under dry conditions. The thickness formula [9] may be stated as follows

$$\frac{h_o}{R} = (3 \to 4.5)\left(\frac{W}{E'R}\right)^{\frac{1}{4}}\left(\frac{\eta}{E't}\right)^{\frac{1}{2}}$$

Using the assumed values for the parameters, the minimum film thickness of the synovial joint during the squeeze action is presented in table (1). The thickness of fluid film separating the articulating surfaces is reduced with time as a result the continuity of this loading conditions for long time lead to contact the asperities of the articular cartilage. But because physiological loading do not damage the joint, the next phase in the walking cycle will reduce the load result in sucking the lower molecular weight elements into the joint interface by the hydrodynamic action. And this really what happens in the second period of the stance phase, i.e. after heel strike, where the weight transfer occurs. At this period the load is reduced to that in heel strike but its value is considerably high about 1350 N, when comparing this load with that applied during the swing phase, combined with a sliding velocity of about 0.17 m/s. as a result of these conditions elastic deformation of the articular surface will occur and the lubrication mechanism activated at this stage is elastohydrodynamic lubrication, which support the joint for about 0.5 sec.

The minimum film thickness calculated under these conditions is that predicted by [21],

$$\frac{h_o}{R} = 1.3\sqrt{\frac{2\eta U}{E'R}}$$

The values of minimum film thickness for each phase in the walking cycle are calculated each with its appropriate formula and tabulated in table (1).

One method of assessing the likelihood if an effective fluid-film lubrication in bearing is to estimate the ratio of the predicted film thickness to the composite surface roughness (R^a) of the unloaded solids. If (h/R_a) is less than unity then boundary lubrication must be anticipated, the value of surface roughness of the articular cartilage seems to range from $(2\text{-}20)*10^{-8}$ m [6]. This ratio is calculated for each mechanisms of lubrication during different phases of walking cycle to demonstrate the effectiveness of the lubrication system.

The calculations related to the knee joint during walking cycle, as shown in table (1), indicate that synovial joints are fully fluid film lubricated. The fluid film is a squeeze film under normal loading conditions and elastohydrodynamic film when sliding or rolling occurs: the elastohydrodynamic supplies the squeeze film. Therefore, phenomena such as weeping of cartilage and the boundary lubrication characteristics of synovial fluid on cartilage play secondary roles in healthy synovial joints.

The film thickness for both static squeeze and the elastohydrodynamic feeding are affected by critical parameters: (R/E), the product of conformity and compliance of the surfaces, and the viscosity of the synovial fluid. These parameters permit rationalizations concerning why joints fail with age and why prosthesis is poor substitutes for properly functioning natural joints.

Let us consider these parameters and its effects on the film thickness:

1. The parameter (R/E) appears most subject to change due to aging, injury, and disease. Lesions would locally change (R/E) producing leakage paths from the squeeze film load support zone and decreasing film thickness. In addition, they would increase stress on the cartilage at the edges of the damaged area. Thus, it should be the aim of mechanical engineering and the medical professionalists to do every thing possible to maintain joint conformity and compliance (R/E).

2. Changes in synovial fluid viscosity also would affect film thickness. However, pathological changes in synovial fluid cause a depolymerization of hyaluronic acid complexes, the consequent decrease in viscosity and change in rheological type of synovial fluid will impair lubrication.

When the pathological changes take place in the articular cartilage, the following mechanism is possible:

1. Decrease in resiliency and smoothness of articular surfaces will lead to direct contact and conditions of boundary lubrication.
2. A decrease in normal and lateral deformations of the cartilage will cause a large increase in the local pressures within the joint and lubricant, as the film thickness will be reduced many times.

Analysis the Performance of Synovial Joint During the Swing Phase and Weight Transfer Phase:

An equivalent bearing was specified to represent the knee joint for the hydrodynamic and elastohydrodynamic lubrication analysis. The conjunction between the femur and tibia in the knee joint can be represented by an equivalent cylindrical elastic component near a plane. The load and sliding velocity in the knee joint for a swing phase and weight transfer phase of a walking cycle was taken from figure (2), [5,8].

1. Hydrodynamic lubrication

The hydrodynamic theory of lubrication for rigid cylindrical surfaces lubricated by an isoviscous lubricant was solved previously and gives the following figures for the pressure distribution and film thickness.

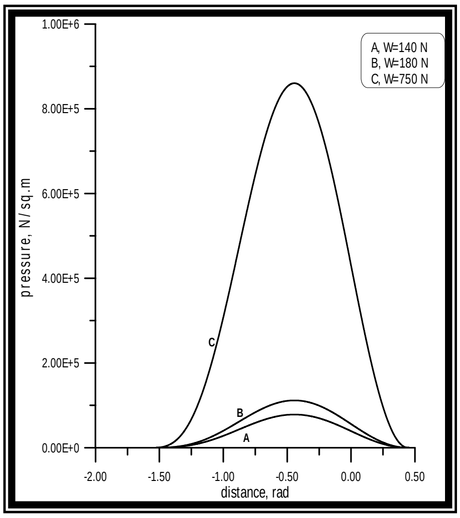

Figure-5: pressure Distributions for Different joint force (w).

Figure (5) represents the pressure distribution in synovial joint operating under hydrodynamic lubrication conditions, the range of loads applied during the swing phase of the walking cycle with its concerned velocity was chosen from table (1), which represents the input parameters for the hydrodynamic lubrication system. As shown in figure (5), the value of the applied load on the joint has a profound effect on the value of pressure that are developed, i.e. when the load is low the developed pressure is low and when the load is high, the pressure is high. But in general, we see that the maximum load applied during the swing phase is 750 N that results in a pressure distribution with a peak value 860.449 kN/m2.

Figure (5) gives the following indication: as soon as the surfaces are set in motion, the fluid becomes drawn into the contact by the action of purely viscous forces. The hydrodynamic pressure in the fluid layer will appear in the inlet of the contact region and propagate further into the contact

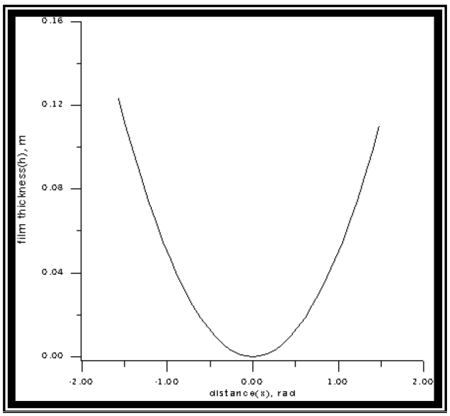

Figure-6: Hydrodynamic Film Thickness Profiles

Figure (6) represents the curve of film thickness. The profile of this curve indicates that there is a region where the film thickness is very small, denotes as the minimum film thickness. It is interesting to notice that the applied load affects the value of h_o, when the applied load is increased the value of h_o is decreased and the danger of contact may occur. But because the bony ends in synovial joint are covered by articular cartilage, which is a soft material, elastic deformation of the moving surfaces will occur, which results in increasing the area at which the load applied to it resulting in building up a pressure equilibrate the applied load and providing a film thickness preventing the contact. In other words another theory of lubrication will be operated, which is elastohydrodynamic lubrication theory.

3. Elastohydrodynamic lubrication

For the elastohydrodynamic lubrication problem the analysis takes another form. In such contacts the film formation is strongly affected by the lubricant behavior and the elastic deformation of the bearing surfaces.

It should be pointed out that 131 uniform nodes were used for the solution of this system. It took about 15 iterations to obtain a convergent solution. Great care was taken to make sure that sufficient nodes were placed to ensure a smooth profile as was done. It is found that the grid structure is very important to the solution. If too course a grid were used, the film thickness would be underestimated and some oscillation in the pressure profiles would be observed.

The location of the outlet, x_o, beyond which the Reynolds equation is no longer valid, is determined along with the pressure distribution and film profile. The pressure value at the grid point adjacent to x_o is monitored. If this pressure value is negative, x_o is moved towards the upstream by one grid space. If the pressure value is positive, x_o is moved towards the downstream by one grid space. Thus, the outlet location is determined to the nearest grid point.

Generally, the solution procedure for elastohydrodynamic problems begins by assuming a starting pressure distribution that approximately balances the applied load, hertzian pressure distribution, with a unity maximum pressure (P_H). Then, the initial value of pressure is determined by the difference between this assumed pressure and the actual pressure, the pressure obtained by solving the Reynolds equation. Then this value of pressure is updated with the assistance of the relaxation factor until reaching the convergent solution.

Firstly, the solution of this mechanism of lubrication is done by using algorithm that combine the direct-iteration and Newton-Raphson methods, results are presented in dimensionless form, figures (8) and (11).

Results presented in figures (8) and (11) give a good agreement with that presented by Hamrock et al. [23], where the distribution of pressure is limited between (-1.5, 1.5). The pressure reached its maximum value at x =0, then it decrease gradually until it becomes zero at x=1, this represents the characteristic feature for the isoviscous elastohydrodynamic regime [4, 23].

After examining the algorithm, by comparing the dimensionless result with that presented by Hamrock et al. [23], now we can use this algorithm to estimate the pressure developed in the synovial joint, knee joint, and the profile of synovial film thickness during the weight transfer phase.

Figures (9) and (10) represents the pressure distribution of the synovial joint for different loads.

For figure (9), the applied load is 1350 N results in a pressure distribution with a maximum value of 146.504 kN/m^2. Figure (10) presents elastohydrodynamic pressure equal to 97.6801 kN/m^2 coincides with the applied load equal to 600 N.

Figure (11) represents the profile of film thickness for an isoviscous compressible line-contact elastohydrodynamic lubrication problem. It should be pointed out that the synovial film was flattened in the load bearing area, in order to increase the area at which the load applied.

The film thickness during the Hertzian pressure distribution, figure (7), can be described as a flat film (parallel to the x-axis) at the area limited between (-1, 1), while the film thickness increased gradually out of this limit, at the periphery. This film profile is updated according to the effect of the pressure generated within the joint resulting in a synovial film shape as that presented in figure (12). For such figure, it should be noted that the gap was only slightly present, and this because that the effect of viscosity on the pressure developed in the lubricant was ignored [4,23].

Studying the profile of the pressure distribution and film thickness in elastohydrodynamic lubrication analysis for knee joint did not shed light previously, so this study represents one of the preliminary studies in this field but It should be pointed out that the solutions presented in this section is for an isoviscous compressible line contact problem, whereas synovial joint lubricated by an isoviscous incompressible elastohydrodynamic regime, so algorithm that solved isoviscous incompressible line contact problem was not available for us, so we assumed the lubricant to be compressible to achieve the solution for the problem, but Hamrock et al. [4,23] demonstrated that the difference in pressure and film thickness between the compressible isoviscous and incompressible isoviscous solutions was so small or negligible.

Conclusions:

For the hydrodynamic lubrication analysis it can be concluded:

- The position at which the maximum pressure located is equal to -0.4432959 rad, which is the same for different loads.
- The loads applied during the swing phase ranged between (40 – 750) N resulting a hydrodynamic pressure ranged between (20.6151 –860.449) kN/m^2 and minimum film thickness ranged between (0.3658 – 1.8)*10^{-6} m.

  For the elastohydrodynamic lubrication analysis it can be concluded:

- The loads applied during the weight transfer phase ranged between (600 – 1350) N resulting a hydrodynamic pressure ranged between (97.6801 –146.504) kN/m^2 and minimum film thickness ranged between (2.5 – 3.57)*10^{-6} m.

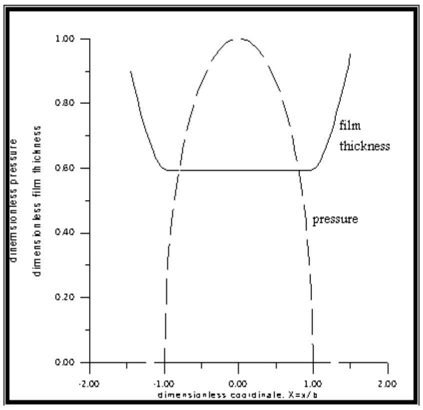

Figure -7: Hertzian Pressure Distribution and Film Shape.

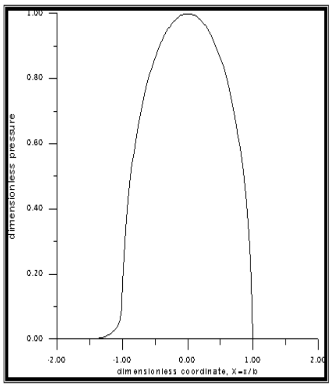

Figure-8: Dimensionless Pressure Distribution at W=3*10^{-4}

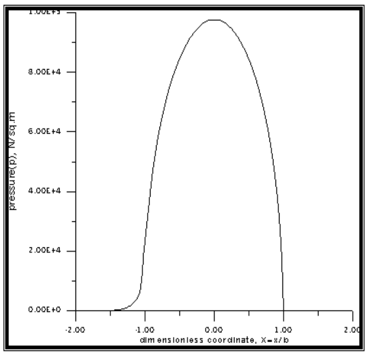

Figure-9: Synovial Joint Pressures at w =1350

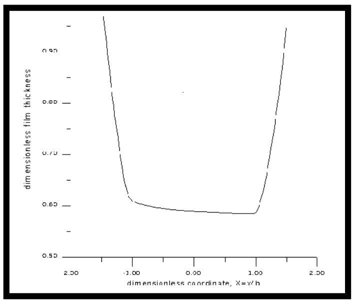

Figure-11: Dimensionless Film Thickness at $W=3*10^{-4}$

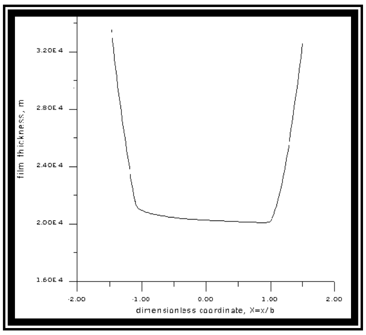

Figure-12: Synovial Joint Film Profile at w =1350 N.

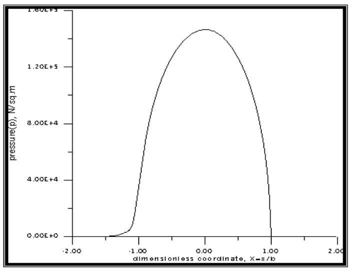

Figure-10: Synovial Joint Pressures at w =600 N.

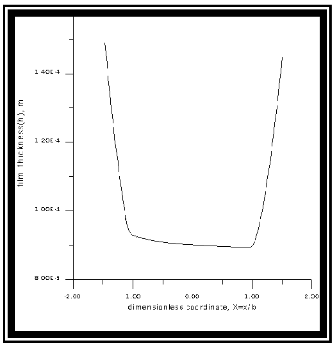

Figure -13: Synovial Joint Film Profile at w =600 N.

Table 1.1. Analysis of the Walking Cycle

Lubrication Theories	HD			SQ.	EHD					SQ.	HD
walking cycle (sec)	0.1	0.2	0.3	0.35	0.4	0.45	0.5	0.6	0.7	0.84	1.1
Force (N)	40	180	750	1750	1350	680	1300	600	750	1750	140
Sliding velocity (m/s)	.074	.23	.28	0	.175	.175	.086	.12	.11	0	.22
h_o (μm)	1.81	1.25	.365	6.26	3.57	3.57	2.5	2.96	2.8	4.09	1.54
$\frac{h_o}{R_a}$	9.05	6.25	1.82	31.3	17.85	17.8	12.5	14.8	14	20.4	7.8

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دور ميكانيكيات التزييت في مفصل الركبة ألزليلي

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الخلاصة:

المفاصل الزليلية تمثل الميزة الأساسية و الأكثر أهمية في جسم الإنسان وذلك بفعل الدور الذي تلعبه في حركته فهي مخصصة لنقل أحمال كبيرة وفي نفس الوقت تسمح بحركة نسبية للعظمين المتمفصلين. بالرغم من هذه الظروف المعقدة فأن المفصل ألزليلي يبقى كفؤ لفترة طويلة، مما يؤكد وجود نظام تزييت فعال يمنح المفصل حرية الحركة و بدون ألم.

انطلاقا من الدور الذي يلعبه نظام التزييت في كفاءة المفصل وديمومته انشأ هذا البحث، والذي اهتم بدراسة أنظمة التزييت التي تعمل في المفصل الزليلي. بصورة أساسية، فان الهدف من هذا البحث هو تقديم تحليل هندسي شامل لشكل طبقة المزيت الزلالي وتوزيع الضغط المتولد في المفصل نتيجة عمل نظريتي التزييت الهايدروديناميكية و الهايدروديناميكية المرنة.

النتائج أظهرت انه في تأثير النظرية الهايدروديناميكية يتراوح اقل سمك للسائل الزليلي بين(٠.٣٤ و١.٦٧) مايكرومتر و الضغط المتولد في المفصل نتيجة عمل هذه النظرية يتراوح بين(٢٠,٦١٥١و ٧٨٢,٨٧٦) كيلونيوتن/متر٢. بينما تأثير النظرية الهايدروديناميكية المرنة يتراوح اقل سمك للسائل الزليلي بين(٢.٥ و٣.٥٧) مايكرومتر و الضغط المتولد في المفصل نتيجة عمل هذه النظرية يتراوح بين (٩٧,٦٨٠١ و١٤٦,٥٠٤) كيلونيوتن/متر٢.

أخيرا، وجد انه تحت ظروف معينة فان نظريتي الهايدروديناميكية والهايدروديناميكية