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Influence Of Gait Cycle On Lubrication Of Synovial Human Knee Joint

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Abstract— *The geometric, kinematic conditions in synovial human knee joint (journal bearings) are introduced and the basic properties of the gait cycle (stance phase- swing phase) reviewed. Evaluation of film parameters in (hydrodynamic- squeeze- elasto hydrodynamic- boundary) with using new formula introduced. Film thickness for each lubrication type was calculated based on the physical and geometric characteristics of each type that different in aging or injury, relationship properties of gait cycle with the teaching of lubrication are the discussion.*

Keywords— *synovial human knee joint,(hydrodynamic- squeeze- elasto hydrodynamic- boundary), gait cycle*.

1. Introduction

Various intellects on the mechanism of lubrication in human knee joint have been advanced in the paper. Hydrodynamic [1, 2] boundary and weeping [3] lubrication were suggested. The conditions the different regimes are encountered will be discussed and the characteristics of each mode of lubrication will be qualified. The hydrodynamic theory will be applied to the conditions in knee joints and the possibility of fluid film formation will be examined. Explanations for joint failures due to aging or injury and the failure of prostheses are rationalized in terms of reducing the thickness and increased stress resulting from a reduction of conformity and compliance of joint surfaces. Engineering - lubrication theory applied to the knee and hip joints indicates that synovial joints are fluid film-lubricated [4]. The fluid film is a squeeze film under normal loading conditions and elasto hydrodynamic film when sliding or rolling occurs; the elastohydrodynamic actions supplies the squeeze film. Therefore, phenomena such as Weeping of cartilage, in-Hooklan properties of cartilage, and the boundary lubrication characteristics of synovial fluid on cartilage play secondary roles in healthy synovial joints. Changes are synovial fluid viscosity also would affect film thickness. However, the comparatively small decreases in viscosity due to trauma and disease have much lesser effects on film thickness than those due to conformity and compliance. However, pathological changes in synovial fluid cause a breakdown of macromolecular or depolymerization of hyaluronic acid complexes. the consequent decrease in viscosity and change in the rheological type of synovial fluid will impair lubrication. Kinematic describe synovial knee joint depended on gait cycle that divides depending on the type of motion (stance phase – swing phase), type of lubrication in a stage of walking.

2. Gait cycle [5]

Human gait may be defined as “the translatory progression of the human body as a whole, produced by coordinated, rotatory movements of the body segments” is known as gait or human locomotion.

2.1 A phase of the gait cycle

During the `gait cycle, each extremity passes through two major phases

1. Stance phase----60%
2. Swing phase-----40%

- There are two periods of “double support” in which one extremity is in the initial contact and the other one leaves the ground
- At normal walking speed, each period of double support occupies 11% of the gait cycle which a total duration of 22% of the gait cycle, normally 20% is used
- The body is supported on a single limb for a duration which makes 80% of the gait cycle.

3. Film Parameter

The film parameter is used to classification the four important lubrication regimes of a synovial human knee joint, this classification depended on surface roughness of articular cartilage, a viscosity of the synovial fluid, a mass of male and female and cycle time in a normal walk. see table (1.1) describes the range of values for the four lubrication regimes see. The relationship between them is:

$$\square = \frac{3 * \sqrt{R_a{}^2 + R_b{}^2}}{m * \eta} n. 1.4 \qquad 1.1$$

R_b the roughness of two articular cartilages, Where n is number of cycle time, R_a

Table (1.1): Film thickness regimes

Regimes	Hydrodynamic Lubrication	Squeeze lubrication	Mixed Lubrication	Boundary Lubrication
Specific film thickness	(□ > 5)	(1.5 <□ < 5)	(0.7 < □ < 1.5)	□ < 0.7

3.1 Effect of Mass

mass of person(male and female) is very important to determine film parameter is a type of lubricant, increase the load on synovial human knee joint leads to decrease file parameter with increase cycle – time. With the progress of the human age loses a proportion of the muscle, which reduces the burning of fat and calories, especially female therefore different film a

Table (1.2) :Relationship between mass &film parameter

mass (kg)	Film parameter after 1- cycle	Time (s)	Film parameter after 20- cycle	Time (s)	Film parameter after 150-cycle	Time (s)	Film parameter after 250-cycle	Time (s)	Film parameter after 1000-cycle	Time (s)
	Hydrodynamic lubrication				Squeeze lubrication		Mixed lubrication		Boundary lubrication	
50	59.39	1.4	37.56	28	5.502	210	1.551	350	0.56	1400
60	49.49	1.4	31.30	28	4.535	210	1.292	350	0.46	1400
70	42.42	1.4	26.83	28	3.930	210	1.108	350	0.35	1400
80	37.11	1.4	23.4	28	3.439	210	0.969	350	0.31	1400
90	32.99	1.4	20	28	3.057	210	0.861	350	0.28	1400
100	29.69	1.4	18	28	2.751	210	0.775	350	0.25	1400
110	26.99	1.4	17	28	2.501	210	0.705	350	0.25	1400
120	24.79	1.4	15.65	28	2.297	210	0.646	350	0.23	1400
130	22.84	1.4	14	28	2.116	210	0.596	350	0.21	1400

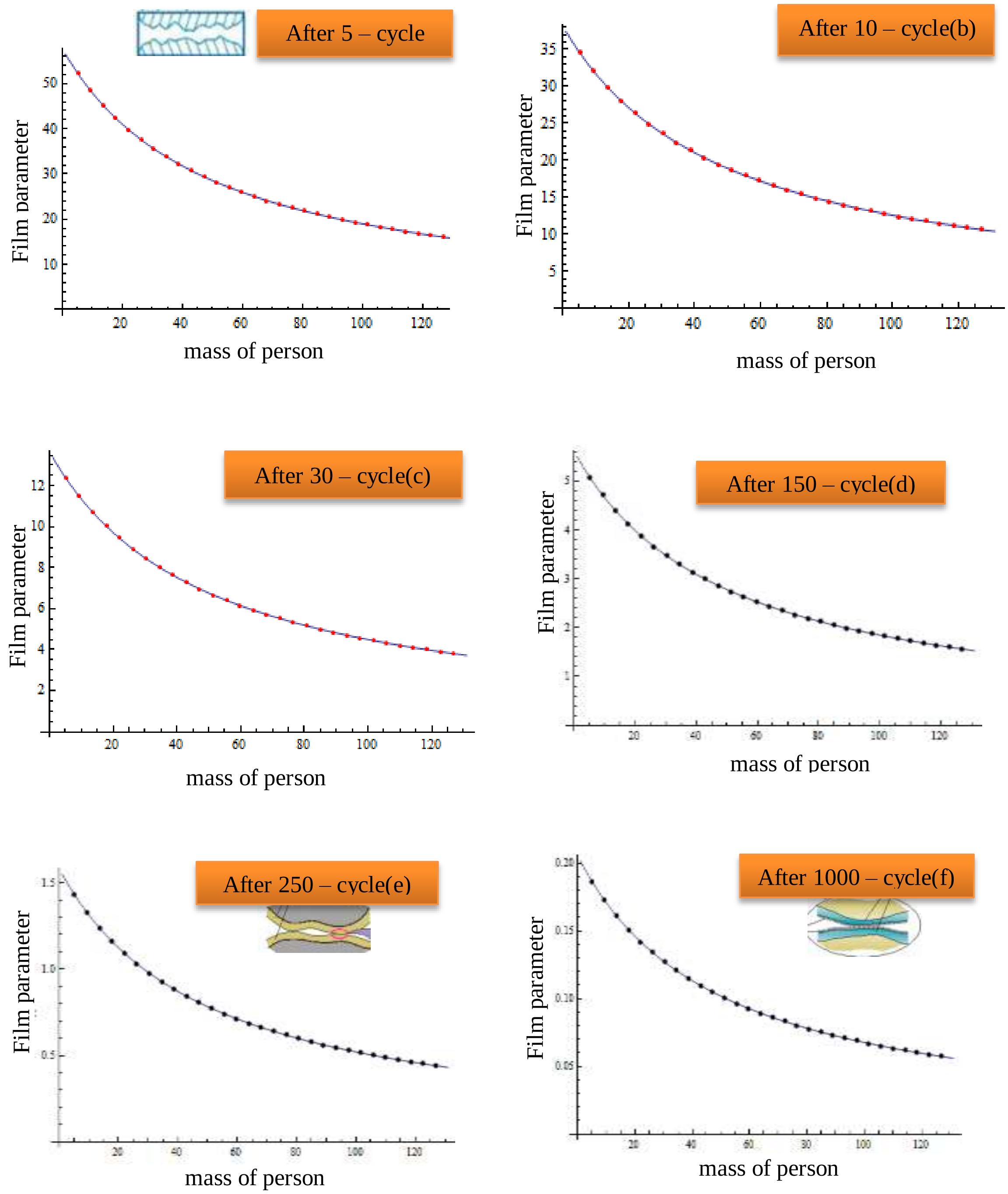

Figure (2.6) Classification of film parameter in(a, b ,c) hydrodynamic ,(d) squeeze ,(e) mixed and(f) boundary lubrication during normal walk.

3.2 Effect of surface roughness

Surface roughness of articular cartilage in knee joint effects on value of film parameter of different regime lubrication , Age is the most important cause of knee roughness, where arthritic erosion increases which results in a decrease in synovial, In the youth

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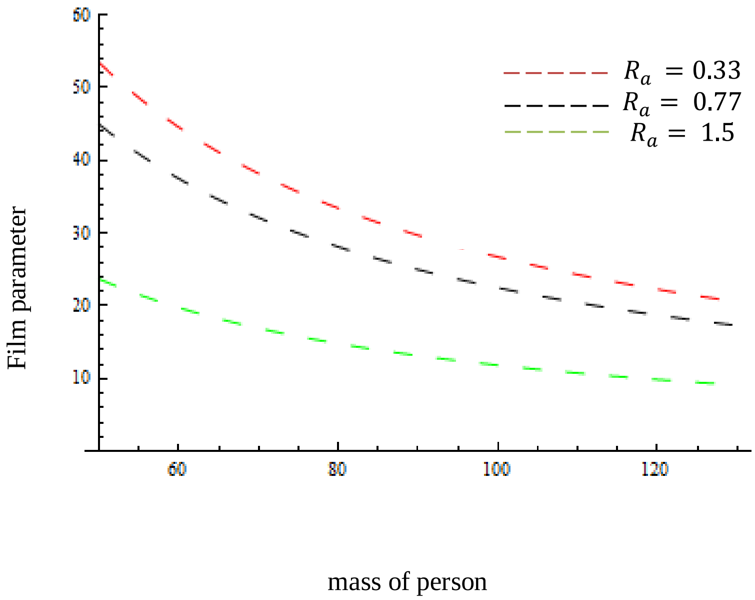
phase, the ratio of roughness is very low and the proportion of fluid produced from the cells is synovial 90 % , After the age of fifty the rate of knee surface increase, especially among female and synovial production, is reduced to 36%



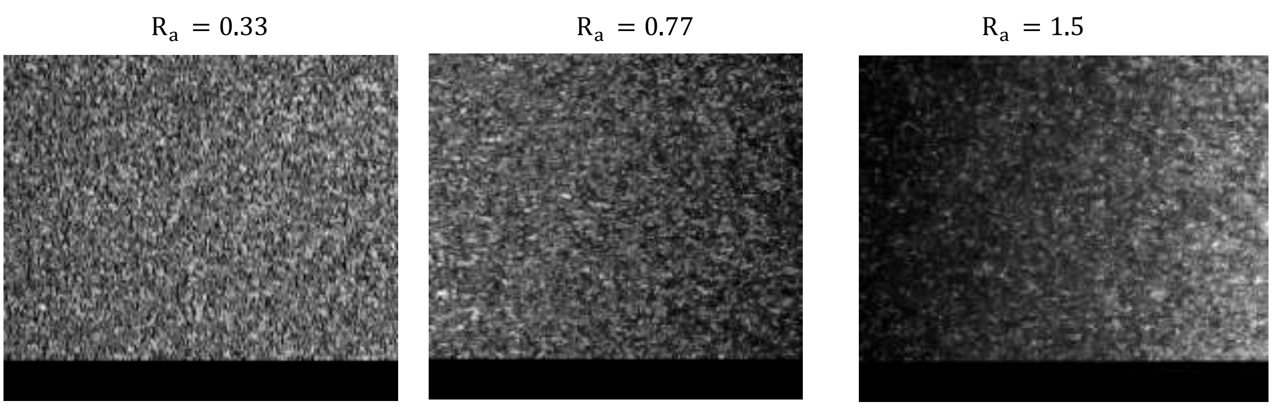


Figure (2.7) shows that the relation between the lubrication parameter and lubrication regimes.

3.3 film thickness Calculation in hydrodynamic lubrication

Calculation film thickness in hydrodynamic lubrication during swing pleas depended on the speed of walk and viscosity of synovial fluid that lubricates surface articular cartilage additional that curvature of the cartilage surfaces and Hand weights on the synovial knee joint, the law of film thickness be:

$$h = \frac{U*\eta}{R*W} \qquad (2.2)$$

3.3.1 Effect of Speed of walk

Walking fast and active helps control weight better than walking at a slow pace; it burns a large number of calories and forms muscle, The man's speed of walk differs from the woman because of the physical structure of each, where there are many structural and sexual differences, where step length and stride length for male more than female As a result, the thickness of the membrane is different in hydrodynamic lubrication and the difference is evident in the youth period, where the percentage of membrane thickness

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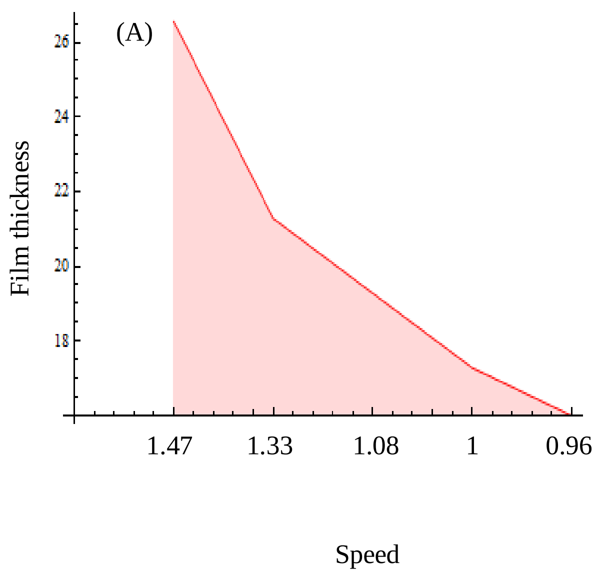
for male was 55% while percentage of membrane thickness for female was 47 %, This difference in speed walk decreases in aging for both sexes due to lack of movement and weight gain

Table 2.3: shows the film thickness for male and female at normal walking speed.

Age	Gender	Speed (m)	Film Thickness	Gender	Speed (m)	Film Thickness
20-29	F	1.47	23.52	M	1.66	27.56
30-39	F	1.33	22.08	M	1.38	23.28
40-49	F	1.08	17.28	M	1.19	19.28
50-59	F	1	16.33	M	1	17.28
60-69	F	0.96	13.36	M	1.08	16.12



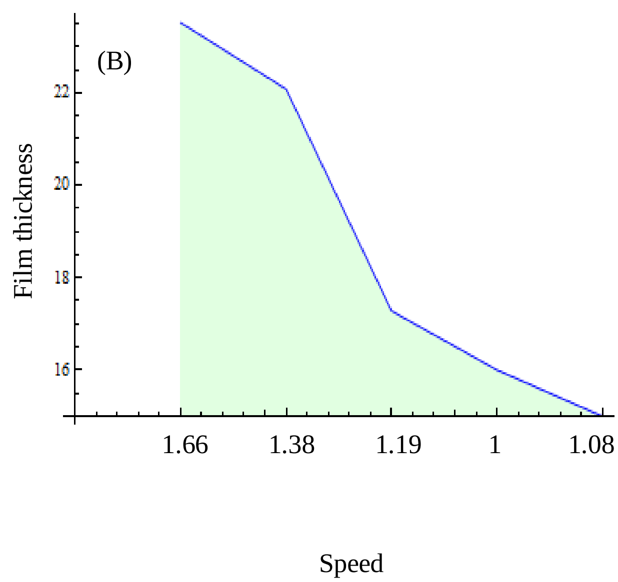


Figure (2.8) shows that relation between film thickness and speed of walk for (A) female and(B) male

3.3.2 Effect of viscosity

Viscosity of the factors affecting the in film thickness of hydrodynamic lubrication ,in swing phase (Initial swing (acceleration), Mid-swing and Terminal swing (deceleration), The pressure in the fluid film is generated because of relative motion of surfaces and wedge action, where describe relative motion of flow synovial fluid between articular cartilage with laminar flow ,pressure in swing phase be simple therefore gravity force between particular be decreasing so viscosity. viscosity different through swing phase where in Initial swing (acceleration) viscosity be high so film thickness while Terminal swing (deceleration) viscosity below so film thickness see figure (2.9), the difference in sex is linked to the thickness of the membrane since the muscle strength in men is greater so the pressure on the joints is lower and the viscosity of the fluid is greater and the thickness of the membrane is greater in men than women see figure (2.10)

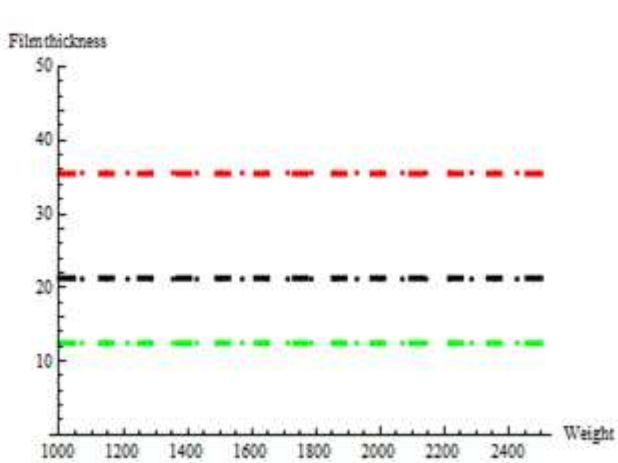


Figure (2.9) Shows that relation between film thickness and Viscosity for male and female

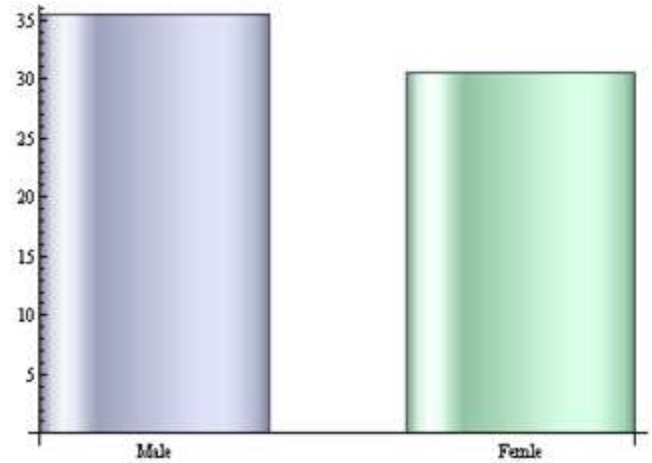


Figure (2.10) shows that relation between film thickness and weight with different Viscosity

3.4 film thickness Calculation squeeze lubrication

Calculation film thickness in hydrodynamic lubrication during swing pleas depended on the speed of walk and viscosity of synovial fluid that lubricates surface articular cartilage additional that curvature of the cartilage surfaces and Hand weights on the synovial knee joint, the law of film thickness be :

$$h = 2.86\sqrt{\frac{\eta}{t}}\left(\frac{R}{E}\right)^{\frac{2}{3}} \qquad (2.3)$$

3.4.1 Effect of time

Time is very important in technique lubrication in the stance phase (initial contact) flow synovial fluid from synovial cell to gap between two articular cartilage where squeeze due to loads on knee joint .this compression varies with different walking stages and cycles where in (1– cycle) squeeze reach to 1.51in initial contact while (8–cycle) squeeze reach to 34.35 in loading response.

Table (1.4): show the relationship between squeeze lubrication and tasks of the Gait Cycle

Time	Cycle	Film Thickness	Squeeze	Tasks of the Gait Cycle	Period
1.40	1	0.924	1.51	Weight acceptance	initial contact
2.80	2	0.653	4.30		
4.20	3	0.533	7.87		
5.6	4	0.456	12.28		
7	5	0.4133	16.93		
8.4	6	0.377	22.28		
9.8	7	0.349	28.08		
11.2	8	0.326	34.35		loading response

After 60 (m)				
Cycle	Film Thickness		Tasks of the Gait Cycle	Period
43	0.049	109	Weight acceptance	loading response
	After 1 (hour)			
86	0.0176	305	Weight acceptance	loading response

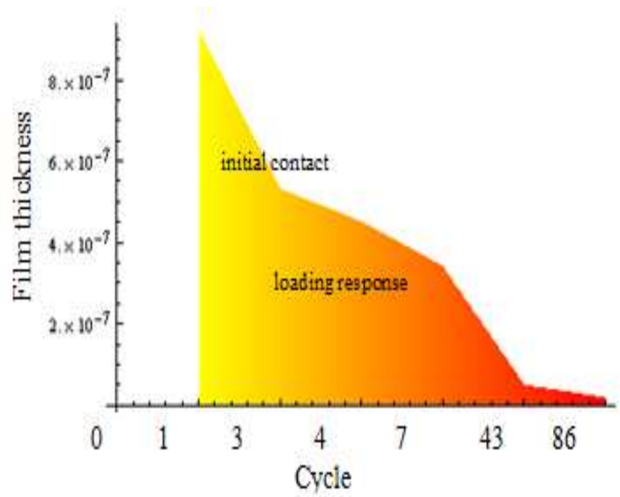


Figure (2.11) shows that the relation between film thickness and cycle time in the gait cycle

3.4.2 Effect of viscosity

The synovial membrane that secretes the synovial fluid, which softens the movement of the joint and facilitates its sliding and protects against shocks. This liquid contains a high proportion of hyaluronic acid, which gives it a vicious and flexible body to perform efficiently, but the inflammation also affects the membrane increases the secretion of synovial fluid, but the proportion of hyaluronic acid responsible for his wife and flexibility, which loses its role and accumulates fluid in the joint causing swelling of the joint.

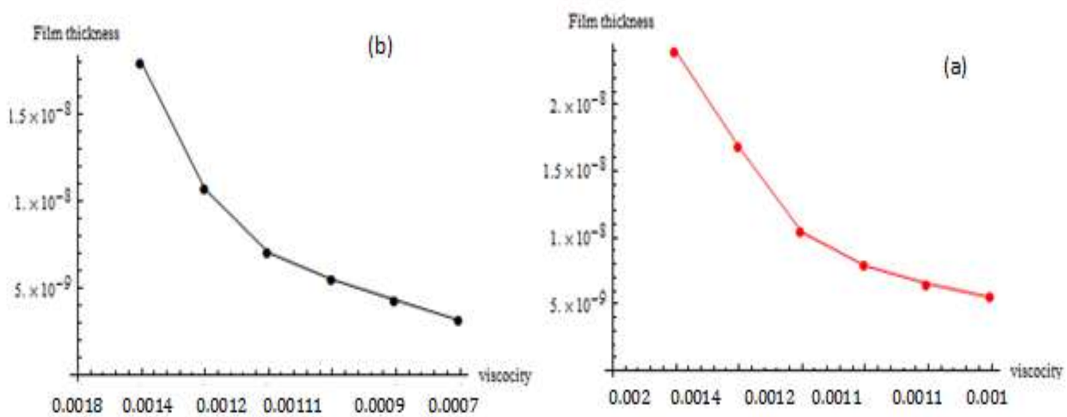


Figure (2.12:) shows that effective viscosity on film thickness after 5 hours of normal walk, (a) normal knee joint (b) disease knee joint.

3.4.3 Effect of a radius of curvature (R)

The curvature of the articular cartilage is connected to squeeze lubrication and load carries capacity in young age (male-female) curvature appears lower since the thickness of the membrane is high, so load carries capacity of articular cartilage. With the age progresses, a curvature of the articular cartilage increases since The inability of the joints on load body weight, which increases with age, that appears more in female over the age of 55 due to physiological reasons.

Table (1.6): Effect speed on the curvature of articular cartilage

(Female)		(Male)	
Speed	Curvature	Speed	Curvature
1.47	0.17	1.66	0.16
1.33	0.211	1.38	0.2
1	0.45	1.19	0.21
0.5	0.54	1.2	0.3

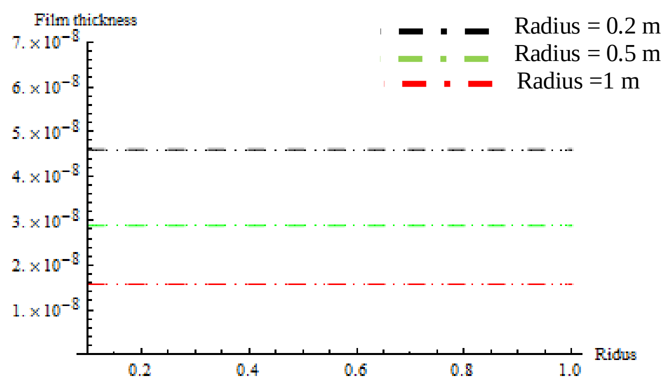


Figure (2.13) Shows that effective curvature of the articular cartilage on film thickness in stance phase

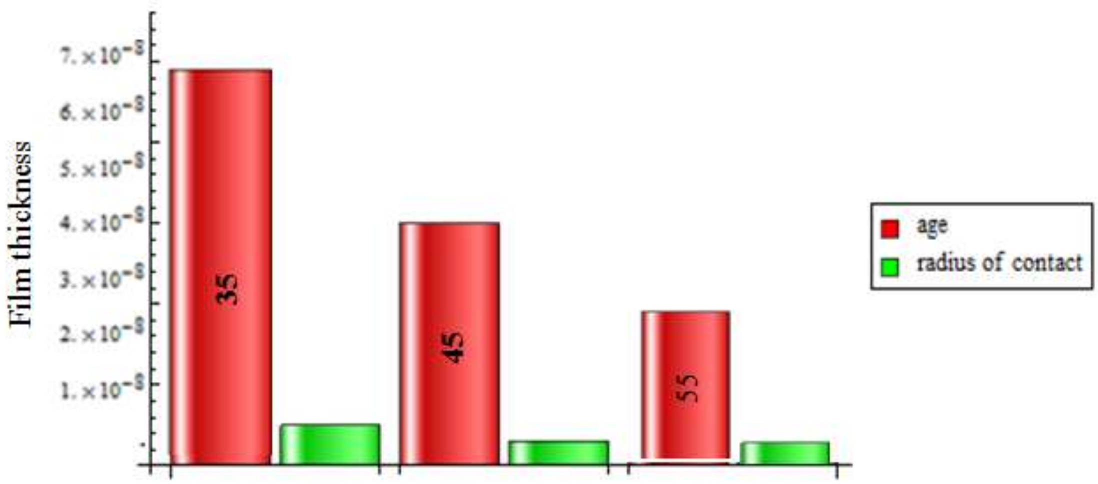


Figure (2.13) Shows effect age and radius on film thickness

3.5 Film thickness calculation elasto hydrodynamic lubrication

Soft elasto hydrodynamic (I-EHL) the lubricant thickness is independent of the lubricant pressure – viscosity characteristics but much more strongly dependent on three main factors :

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1. concentration of Hyaluronic acid in synovial human joint
2. Non-dimensional load on synovial knee joint
3. velocity

To calculates thin of the film in elasto hydrodynamic lubrication during mid-stance in the gait cycle, we have been applied following the form law:

$$\mathbf{h} = \mathbf{AH} * \frac{\mathbf{U}}{\mathbf{W}} \quad (2.4)$$

3.5.1 Hyaluronic acid

Hyaluronic acid The primary function is to maintain the vicious strength of the synovial fluid and reduce the friction between the bones of the joint, different concentration of Hyaluronic acid in synovial human joint depended on two factors (age, health) where high concentration of Hyaluronic acid to 3.9 in age (18-30) year and low in age (45-66) year to reach 2.1. A film thickness of elastic- hydrodynamic lubrication increasing when the concentration of Hyaluronic acid be high and decreeing when the concentration of Hyaluronic acid below, The proportion of this substance decreases in case of disease (rheumatoid - arthritis) thus reduce the thickness of film 0.8 µ

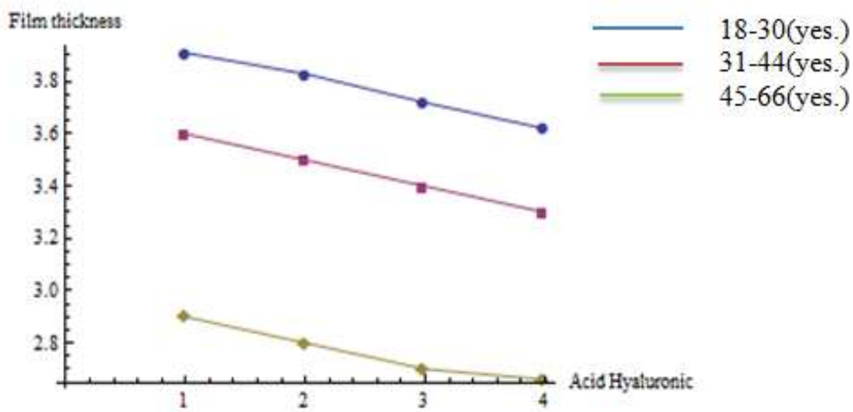

Figure (2.14) Shows, effect Hyaluronic Acid on film thickness in EHL

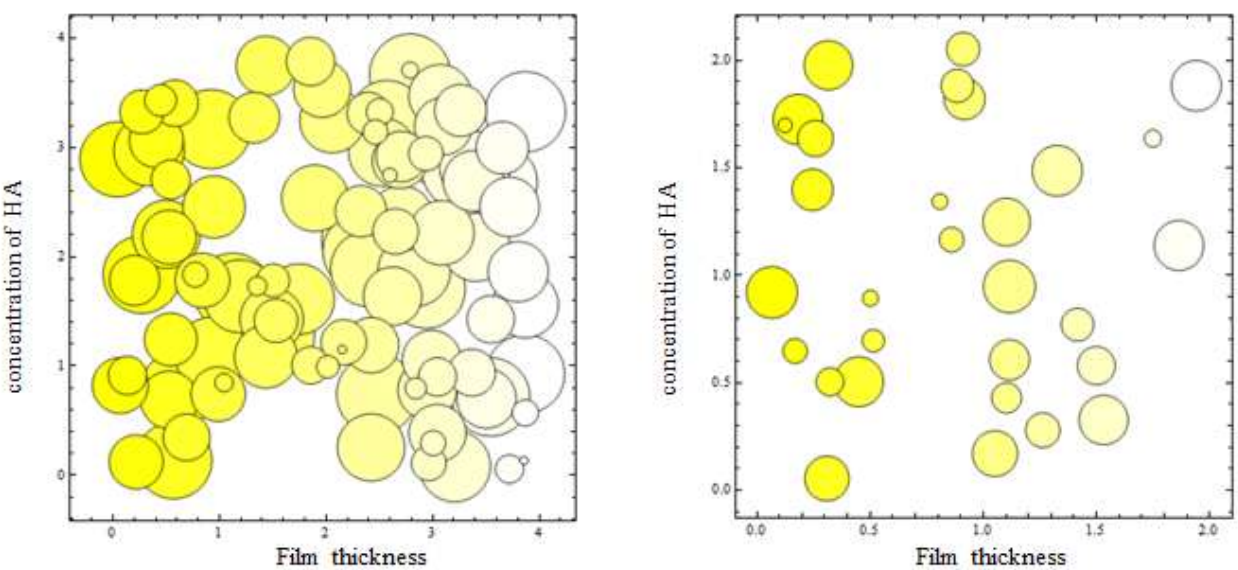

Figure (2.15) Shows, particle lubrication of Hyaluronic Acid (a) normal joint (b)

3.5.2 Non-dimensional load on synovial knee joint

The knee joint is loaded by external forces (ground reaction force, masses and acceleration forces of foot and shank). In mid-stance where one or two foot on ground there are two main factors affect (ground reaction force, masses) where near-surface of articular cartilage of each other and increase radius of curvature, thin of film effect with different load wherein less load activity motion standing up/sitting down then the thickness film ranges between [3.6-1.8] while high load activity motion one-legged stance then thickness film ranges between load [1.7-0.5]

Table (2.7): Effect Non-dimensional load on Film thickness articular cartilage

Non-dimensional load	Activity	Film thickness (μm)
$1{\times}10^{-4}$	standing up/sitting down	3.6
$1.5{\times}10^{-4}$	standing up/sitting down	2.4
$1.6{\times}10^{-4}$	standing up/sitting down	2.15
$1.7{\times}10^{-4}$	standing up/sitting down	2.11
$1.8{\times}10^{-4}$	standing up/sitting down	2
$1.9{\times}10^{-4}$	Knee bend	1.89
$2{\times}10^{-4}$	Knee bend	1.8
$2.1{\times}10^{-4}$	Knee bend	1.71
$2.2{\times}10^{-4}$	Knee bend	1.63
$2.3\ {\times}10^{-4}$	one-legged stance	1.56
$2.4{\times}10^{-4}$	one-legged stance	1.5
$2.5{\times}10^{-4}$	one-legged stance	1.44

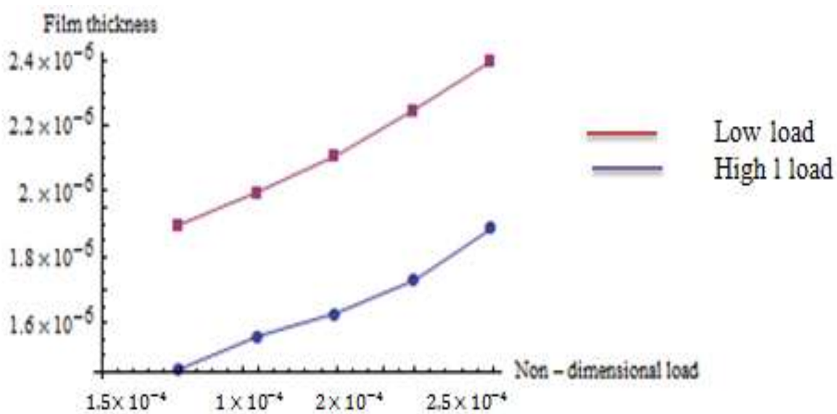

Figure (2.15) Shows, film thickness with different non-dimensional load

3.5.3 Non-dimensional velocity

Classification of motion in midstance to (standing up/sitting down- one-legged stance and knee bend).Therefore different velocity flow synovial lubricant and particle lubrication of porosity articular cartilage, where standing up/sitting down high thin film while decreasing film thickness in on legged stance become low thin-film clear in knee bend, this is due to increased pressure on the knee joint

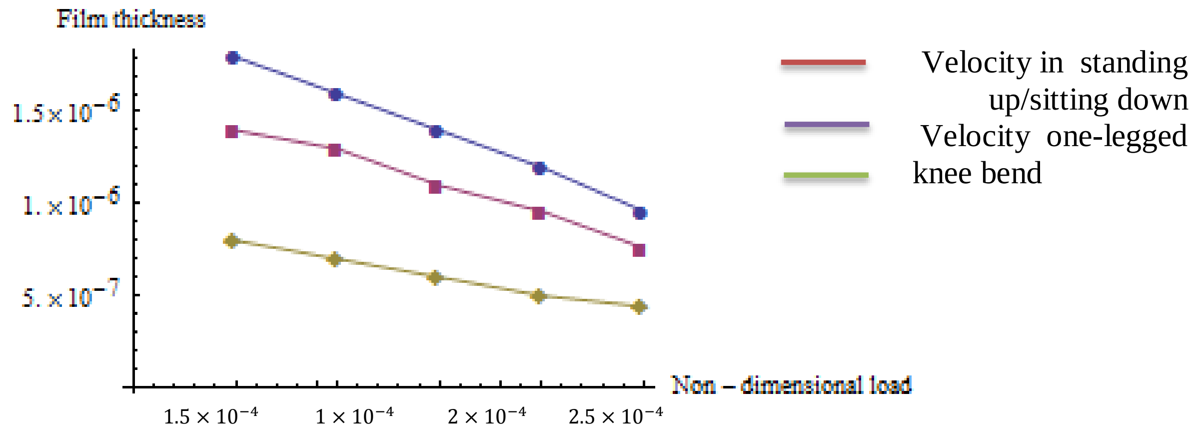

Figure (2.16) shows the variation of film thickness with Hyaluronic acid for different dimensionless velocity in (EHL)

4. CONCLUSIONS

The numerical values of synovial fluid film thickness obtained for the different of types lubrication in synovial human knee joint suggest the following::

1- Analysis of hydrodynamic lubrication in swing phase fluid friction between articular cartilage is less and joint is protected.

2- The viscosity of the synovial fluid in hydrodynamic lubrication the most effect on the thickness of film then speed walk.

3- Gender is also responsible for determining the film thickness count on the walking speed which is higher in male than female.

4- In Squeeze lubrication radius of curvature articular cartilage increasing with cycle time and reduce film thickness.

5- Cycle time is control by Squeeze films and viscosity through initial contact

6- In mid-stance sliding motion and load vary by single limb support and double limb support

7- The thickness of the film varies by distribution non-dimensional load in (standing up/sitting down- Knee bend- one-legged stance)

8- dimensional for rigid surfaces with isoviscous lubricant is inadequate, as it predicts values less the C.L.A values of the articular cartilage surface.

9- Films of elastohydrodynamic lubrication having lower thickness relative to the non-dimensional load on synovial knee joint are operative during normal movements.

10- Elasto hydrodynamic films cannot prevent the surface from connecting with a different non-dimensional velocity which little or no sliding takes place, elastic deformation prevents surface damage and to provide low starting friction.

11. Synovial human knee joint in aging or injury reduced hyaluronic acid weak bones and increasing weight compared with the healthy joint.

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