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Transient elastohydrodynamic lubrication in artificial knee joint with non-Newtonian fluids

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ABSTRACT

This paper presents the transient analysis of a human artificial knee joint under elastohydrodynamic lubrication (EHL) for point contact with non-Newtonian lubricants. The artificial knee joints use ultra high molecular weight polyethylene (UHMWPE) against metal with time-varying speed and load during walking. This numerical simulation employed a perturbation method, Newton Raphson method and multigrid method with full approximation technique to solve simultaneously both the time-dependent Reynolds equation, with non-Newtonian fluid based on a Carreau model, and the elasticity equation.

The general numerical schemes are implemented to investigate the characteristics of elastohydrodynamic lubrication in human artificial knee joints; profiles of pressure and film thickness are determined, with varying material and lubricant properties, applied loads and speeds. The results show that the elastohydrodynamic fluid film thickness between the metallic component of the artificial knee joint and the soft polyethylene bearing becomes larger as the contact area increases and the fluid film pressure decreases. At the beginning of the first walking cycle, the film thickness is lower than in subsequent cycles because of the time required to develop the fluid film; after the first cycle, the fluid film is similar for every cycle and is dependent on transient applied load and speed during human movement.

1. Introduction

Although total knee joint replacement enables over 500,000 patients each year to walk without pain after surgery, the knee replacements often fail within 20 years after implantation, necessitating replacement surgery. The most important causes of failure are related to UHMWPE wear. The wear of the polyethylene bearings can be greatly reduced by improving the fluid film lubrication, so it is important to predict the magnitude of lubricating film thickness in artificial knee joints. Several theories and models have been used to study characteristics of artificial joint lubrication. Jalali-Vahid et al. [1,2] used an EHL model for ball in socket configuration to predict the lubrication film thickness in natural and artificial hip joints. The predicted lubricating film thickness in a hip joint replacement with metallic ball in UHMWPE socket is reduced by about 10 percent, compared with the prediction from the corresponding ball-on-plane model. A decrease in UHMWPE elastic modulus led to an increase in the minimum film thickness for the initial machined surface roughness of UHMWPE bearing surface. Murakami et al. [3] presented the fluid film formulation in a knee joint under walking conditions. The lubricating film thickness decreased during the loading period and reduced to the minimum film thickness at the peak load just before toe-off. Jin [4] analyzed the transient fluid film in a knee prosthesis based on an EHL model during walking conditions and validated the simulation result with fluid film thickness measurements from experiment. The effects of geometry of the bearing condylar surface in the design of total knee replacement when subjected to the expected force acting at the knee joint during walking were presented by Walker and Sathasivam [5].

Most of the earlier analysis of joint prosthesis lubrication has assumed that the lubricant behaves in a Newtonian manner, but the actual lubricant in human joints, synovial fluid, is known to exhibit non-Newtonian behavior [6]. In particular, its viscosity is lower at higher shear rates; i.e., it exhibits shear thinning.

In this work, the transient behavior of the lubrication film in an artificial knee joint under point contact conditions between the soft (ultrahigh molecular weight polyethylene—UHMWPE) and hard (Co–Cr alloy) surfaces is investigated through numerical simulation. The transient elastohydrodynamic film thickness distributions in an artificial human knee joint are simulated with both Newtonian and non-Newtonian fluids during typical walking cycles.

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Nomenclature

$C_{UT}(t)$	ratio of velocity in x axis, $C_{UT}=\overline{u}(t)/\overline{u}_0$
$C_{VT}(t)$	ratio of velocity in y axis, $C_{VT}=\overline{v}(t)/\overline{v}_0$
$C_{WT}(t)$	ratio of applied load, $C_{WT}=w_z/w'_z$
$D_x/2$	semi major axis of contact area in x axis (m), $D_x=2(6\xi w_z R/\pi k E')^{1/3}$
$D_y/2$	semi major axis of contact area in y axis (m), $D_y=2(6k^2\xi w_z R/\pi E')^{1/3}$
E_a	elastic modulus of hard surface (Pa)
E_b	elastic modulus of soft surface (Pa)
E'	equivalent elastic modulus (Pa), $1/E'=1/2[(1-\upsilon_a^2)/E_a+(1-\upsilon_b^2)/E_b]$
h	film thickness (m)
H	dimensionless film thickness, $H=hR/(D_x/2)(D_y/2)$
k	ellipticity ratio, $k=D_Y/D_X$
K	constant parameter in Reynolds equation, $K=96\mu_0R^2V_0/P_HD_XD_Y^2$
n	Carreau viscosity exponent index
p	pressure (Pa)
p^*	pressure at the reference condition (Pa)
P	dimensionless pressure, $P=p/P_H$
P_H	Hertzian pressure (Pa), $P_H=6w'_z/\pi D_xD_y$
R	reduced radius of curvature (m), $1/R=1/R_X+1/R_Y$
R_X	radius of curvature in x axis (m), $1/R_X=1/r_{ax}+1/r_{bx}$
R_Y	radius of curvature in y axis (m), $1/R_Y=1/r_{ay}+1/r_{by}$
r_{ax}	radius of curvature of hard surface in x axis (m)
r_{ay}	radius of curvature of hard surface in y axis (m)
r_{bx}	radius of curvature of soft surface in x axis (m)
r_{by}	radius of curvature of soft surface in y axis (m)
t	time (s)
t^*	dimensionless time, $t^*=tV/(D_x/2)$
$u_{a,0}$	velocity of the hard surface in x axis at the reference condition (m/s)
$u_{b,0}$	velocity of the soft surface in x axis at the reference condition (m/s)
$v_{a,0}$	velocity of the hard surface in y axis at the reference condition (m/s)
$v_{b,0}$	velocity of the soft surface in y axis at the reference condition (m/s)
u_a	velocity of the hard surface in x axis (m/s)
u_b	velocity of the softly surface in x axis (m/s)
v_a	velocity of the hard surface in y (m/s)
v_b	velocity of the soft surface in y axis (m/s)
$\overline{u}_0$	average velocity in x axis at the reference condition (m), $\overline{u}_0=u_{a,0}+u_{b,0}/2$
$\overline{v}_0$	average velocity in y axis at the reference condition (m), $\overline{v}_0=v_{a,0}+v_{b,0}/2$
$\overline{u}(t)$	average of velocity in x axis (m), $\overline{u}(t)=u_a+u_b/2$
$\overline{v}(t)$	average of velocity in y axis (m), $\overline{v}(t)=v_a+v_b/2$
V_0	velocity at the reference condition (m/s), $V_0=(\overline{u}_0^2+\overline{v}_0^2)^{1/2}$
V	average velocity of surfaces (m/s), $V=(\overline{u}^2+\overline{v}^2)^{1/2}$
w_z	applied load (N)
w'_z	applied load at the reference condition (N)
W_Z	dimensionless applied load, $W_Z=w_z/E'R_x^2$
x,y,z	Cartesian coordinates (m)
X,Y,Z	dimensionless coordinate, $x=(D_x/2)X$, $y=(D_y/2)Y$, $z=hZ$
z_1	viscosity–pressure index

Greek letters

$\overline{\varepsilon}_U$	constant parameter in Reynolds equation, $\overline{\varepsilon}_U=(\rho H^3)/(\overline{\mu}_{0,u})$
$\overline{\varepsilon}_V$	constant parameter in Reynolds equation, $\overline{\varepsilon}_U=(\rho H^3)/(\overline{\mu}_{0,v})$
λ	time relaxation (s)
μ	viscosity (Pa s), $\mu=\mu_P\mu_S$
μ_P	viscosity from pressure effect (Pa s)
μ_S	viscosity from shear rate effect (Pa s)
$\mu_{L,0}$	low shear strain rate viscosity (Pa s)
$\mu_{L,\infty}$	high shear strain rate viscosity (Pa s)
$\overline{\mu}$	dimensionless viscosity, $\overline{\mu}=\mu/\mu_{L,0}$
υ_a	Poisson ratio of hard surface
υ_b	Poisson ratio of soft surface
ρ	lubricant density (kg/m^3)
ρ_0	lubricant density at pressure ambient (kg/m^3)
$\overline{\rho}$	dimensionless density, $\overline{\rho}=\rho/\rho_0$

2. Governing equations

The transient governing non-Newtonian Reynolds equation and the deformation equation were analyzed to determine the characteristics of the isothermal elastohydrodynamic lubrication. The relationship between viscosity and shear rate of a non-Newtonian lubricant such as synovial fluid in this work can be approximated using a Carreau model as [7]

$$\mu(I)=\mu_{L,\infty}+(\mu_{L,0}-\mu_{L,\infty})(1+\lambda^2 I)^{n-1/2} \tag{1}$$

where

$$I=\left(\frac{\partial u}{\partial z}\right)^2+\left(\frac{\partial v}{\partial z}\right)^2 \tag{2}$$

The time-dependent Reynolds equations with non-Newtonian lubricants can be obtained as [8]

$$\frac{\partial}{\partial X}\left(\overline{\varepsilon}_U\frac{\partial P}{\partial X}\right)+\left(\frac{1}{k}\right)^2\frac{\partial}{\partial Y}\left(\overline{\varepsilon}_V\frac{\partial P}{\partial Y}\right)=K\left(C_{UT}(t)\cos(\psi_0)\frac{\partial}{\partial X}(\overline{\rho}H)+C_{VT}(t)\left(\frac{\sin(\psi_0)}{k}\right)\frac{\partial}{\partial Y}(\overline{\rho}H)+\frac{\partial}{\partial T}(\overline{\rho}H)\right) \tag{3}$$

where

$$K=\frac{96\mu_0R^2V_0}{P_HD_XD_Y^2},\quad \overline{\varepsilon}_U=\frac{\overline{\rho}H^3}{\overline{\mu}_{0,u}},\quad \overline{\varepsilon}_V=\frac{\overline{\rho}H^3}{\overline{\mu}_{0,v}}$$

with the boundary conditions as

$$P(X_{IN},Y)=0,\quad P(X_{OUT},Y)=\left(\frac{\partial P}{\partial X}\right)_{X=X_{OUT}}=0$$

$$P(X,Y_{IN})=0,\quad P(X,Y_{OUT})=\left(\frac{\partial P}{\partial Y}\right)_{Y=Y_{OUT}}=0$$

The dimensionless apparent viscosity in the Carreau model, including a correction factor for the viscosity due to pressure in the lubricant according to Roelands [9], can be written as

$$\overline{\mu}=\frac{\mu_P\mu_S}{\mu_{L,0}} \tag{4}$$

where

$$\mu_P=\exp((\ln\mu_{L,0}+9.67)(-1+(1+5.1\times10^{-9}p)^{Z_1}))$$

$$\mu_S=\mu_{L,\infty}+(\mu_{L,0}-\mu_{L,\infty})(1+\lambda^2 I)^{n-1/2}$$