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LUBRICATION MODEL OF THE HUMAN KNEE IMPLANT

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Abstract: *The number of knee replacement surgeries have increased rapidly over the past few years. However, these implants have limited product life due to the issue of wear. There are numerous difficulties in addressing this problem. The presence of synovial fluid means a complicated lubrication mechanism exists. For the purposes of studying wear, an elastohydrodynamic lubrication model for a human knee implant is presented. Unlike present models that consider circular or elliptical point contact cases, this model will incorporate the irregularity of the knee geometry.*

1 INTRODUCTION

Degeneration is a common occurrence during the lifecycle of a joint, with 3.48 million patients per year in the US alone expected to undergo knee replacement surgeries by 2030 [1]. However, there are numerous issues in current implant designs as they suffer from wear and loosening, together accounting for more than half of knee implant failures [2].

The majority of studies into the wear of implants are experimental in nature [3,4]; numerical modelling has been relatively less explored. To this end, hip implant studies have been carried out extensively [3–7], but knee implants remains relatively unexplored. Unlike the hip implant, which can be approximated as a sphere, the knee implant is much more complex in its geometry. The system is also lubricated between the contact zones and this must be modelled [8].

The increasing number of transplants projected in the future along with the problems mentioned above, provide the motivation for this research. A lubrication model is presented that captures the complex geometry of the knee implant.

2 NUMERICAL MODEL

The knee implant is modelled with elastohydrodynamic lubrication with no simplifications made to the implant geometry. The implant is constituted of two parts, the femoral component and the tibial insert, as shown in Figure 1.

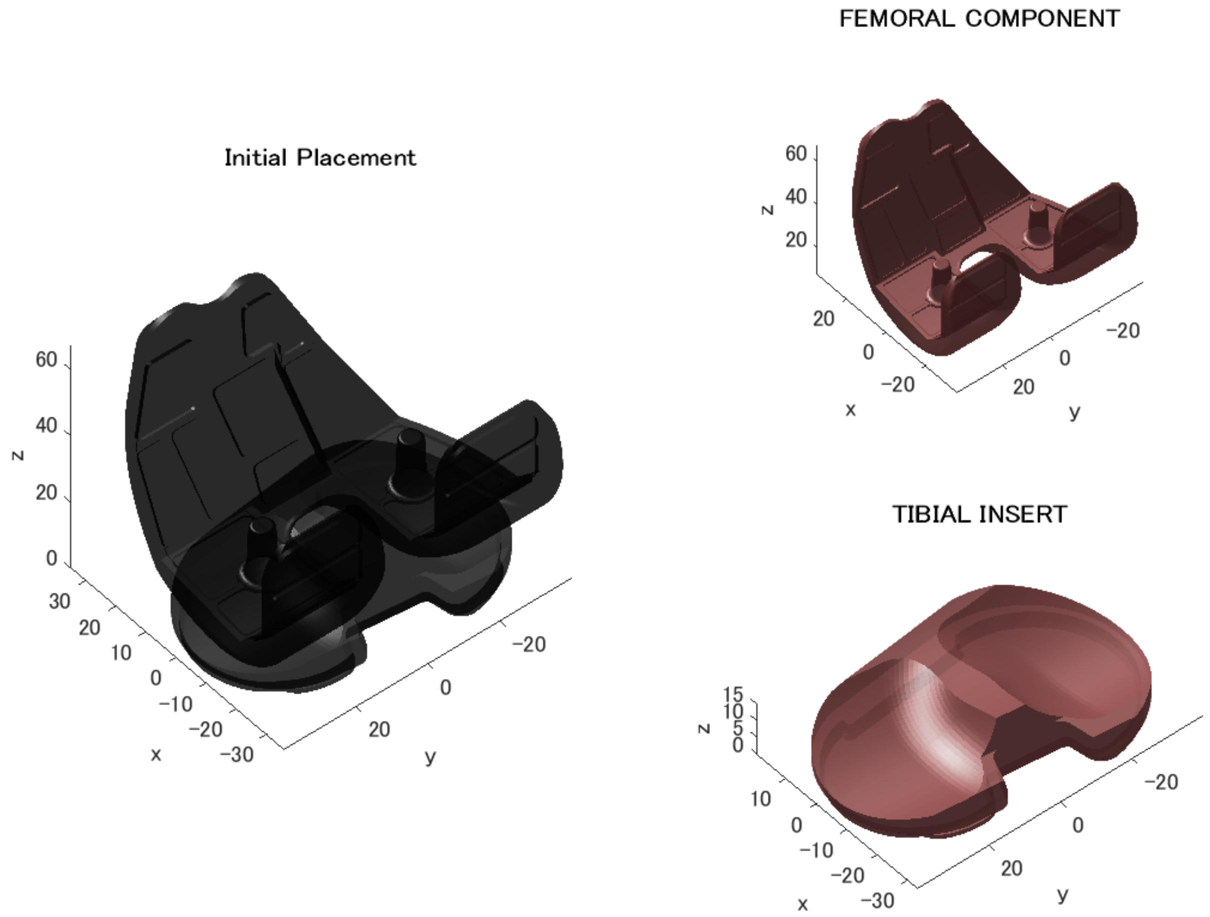

Figure 1: Geometry of the knee implant (in mm) [9]

2.1 Governing Equations

Derived from the Navier-Stokes equation [10], the thin-film Reynolds equation is used to solve the pressure profile:

$$\frac{\partial}{\partial x}\left(\frac{\rho h^3}{12\eta}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\rho h^3}{12\eta}\frac{\partial p}{\partial y}\right)=\frac{\partial}{\partial x}\left[\frac{\rho h\bar{u}}{2}\right]+\frac{\partial}{\partial y}\left[\frac{\rho h\bar{v}}{2}\right] \tag{1}$$

It is assumed that the lubricating fluid is Newtonian and incompressible. The Reynolds equation is coupled with the film thickness equation as follows:

$$h = h_b(\Delta x, \Delta y, \Delta z) - h_a + \Delta \tag{2}$$

h_a represents the geometry of the tibial insert, with h_b representing the femoral component, both in the x, y plane of the Reynolds equation. $\Delta x, \Delta y, \Delta z$ represents the shift in the x, y, z directions of the geometry of the femoral component, made to satisfy the force balance equation (EQ 4). Deformation (Δ) is calculated as follows, with the stiffness matrix (K) calculated from finite element analysis:

$$\Delta = Kp \tag{3}$$

The applied force is balanced in all spatial directions (f_x, f_y, f_z) by integrating the pressure solution across the surface normals (n_x, n_y, n_z):

$$[f_x, f_y, f_z]^T - \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}[n_x, n_y, n_z]^T \, p(x,y)dxdy = 0 \tag{4}$$

2.2 Solution Scheme

A Full MultiGrid (FMG) algorithm was used to solve the system of non-linear equations [11]. Jacobian block relaxation was used to solve the system iteratively. Underrelaxation was used to update both the pressure solution and $\Delta x, \Delta y, \Delta z$ during the iterative process.

As a top-level overview, the relevant equations are solved in the following order till convergence:

(**1**) Evaluate the film thickness equation (EQ 2)
(**2**) Solve the Reynolds equation (EQ 1)
(**3**) Evaluate the load balance equation (EQ 3)
(**4**) Change $\Delta x, \Delta y, \Delta z$ to satisfy EQ 4.

3 RESULTS

Conditions were taken from a typical gait cycle [12,13]. Results for steady cases are presented in Table 1, with select results given in Figure 2. The Young's Modulus for the tibial insert was 1GPa, with a Poisson's Ratio of 0.4. The stiffer femoral component is assumed to have no deformation.

$f_z\ (N)$	$u_x\ (ms^{-1})$	$\eta\ (Pa.s)$	$P_{max}\ (MPa)$	$h_m\ (\mu m)$
100	0.1	0.5	43.84	0.844
100	1.0	0.5	2.25	26.683
100	0.1	1.0	14.82	2.703
100	1.0	1.0	1.35	56.035
500	0.1	0.5	788.94	0.115
500	1.0	0.5	70.63	2.812
500	0.1	1.0	501.15	0.279
500	1.0	1.0	28.16	8.120

Table 1: Showing the minimum film thickness and maximum pressure for different system configurations.

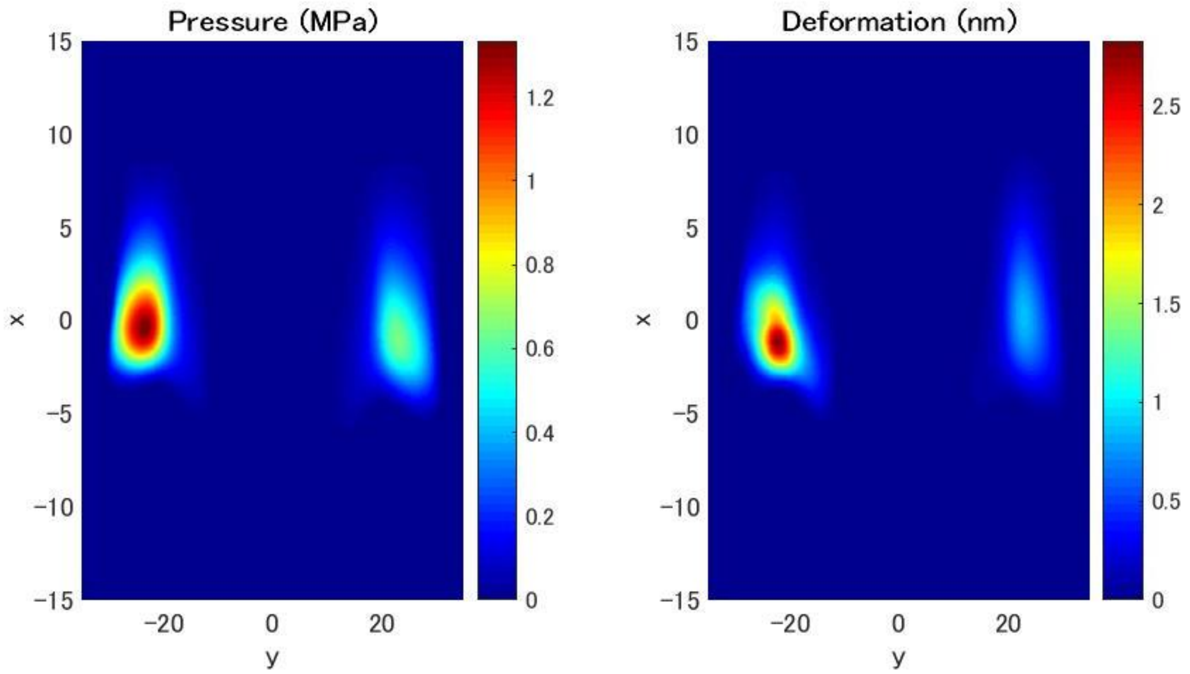

Figure 2: Results for $f_z = 100N, u_x = 1ms^{-1}, \eta = 1Pa.s$ (x and y in mm).

4 CONCLUSIONS

A lubrication model for the human knee implant is solved and the results presented. The solution scheme is stable for the quasi-steady case and balances the load across all three spatial dimensions, with direct geometry representation. This reveals complex pressure field results which differ from those obtained when a geometric simplification (such as a spherical or elliptical contact) is assumed.

The model will be expanded to incorporate surface roughness and mixed lubrication. Transient effects will also be modelled around a typical gait cycle. The complex rheology of synovial fluid will also be incorporated. It is intended to use this model to study wear in knee implants, with the intention to optimize implant design to limit wear.

NOMENCLATURE

p Pressure	$h_{a,b}$ Original geometry of knee implant
h Film Thickness	$\Delta x, \Delta y, \Delta z$ Femoral geometry shift
η Viscosity	Δ Deformation
ρ Density	K Stiffness matrix
x, y Cartesian coordinates	f Applied force
$\bar{u}, \bar{v}$ Average Velocity in x, y	h_m Minimum film thickness

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