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The effect of clearance and wear on the contact pressure of metal on polyethylene hip prostheses

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ABSTRACT

The aim of this paper is to determine the contact pressure, friction torque, and friction energy as a function of clearance and other parameters. The contact pressure is determined without imposing *a priori* a certain distribution law. The wear of the acetabular component modifies the relative clearance of the two bearing surfaces. This fact was observed at metal on polyethylene prostheses explanted during revision surgeries at our orthopaedy–traumatology hospital. For compliant contacts with small clearances, the Hertz theory is not applicable. Therefore, a new model, based on Hills contact theory is developed.

1. Introduction

Nowadays, hip joint arthroplasty is a common operation performed on patients varying from teenagers to elders. One of the most important problems that need addressing is hip implant wear. The distribution of contact pressure in the natural and artificial human joints is an important factor which affects the function of the joint.

As numerous papers show [1–4] the clearance between the two articulating surfaces plays an important role in the friction and wear processes taking place in the prosthesis.

Many authors consider that the contact pressure on the bearing surface of a hip prosthesis varies according to a cosine or a parabolic function [3,5–8]. In all these papers, a parabolic or a cosine variation is *a priori* considered as contact pressure distribution.

The cosine radial pressure distribution [5–7] is based on the assumption that radial pressure in the hip articular surface can be calculated according to Hooke's law [9], i.e. the radial stress in the articular surface of the hip is assumed to be proportional to cartilage thickness.

The parabolic radial pressure distribution [3,8] is based on the Hertzian theory for elastic contact of two bodies with nonconforming geometry. The formulae used are derived for the geometry configuration model that is a sphere in contact with a spherical cavity (ball and socket).

The contact pressure distribution on the hip prosthesis bearing surface is of special interest because it evinces the regions with high stresses. Exceeding the tolerance level of normal cartilage function, the subchondral bone and synovial membrane may cause degenerative changes, leading to osteoarthritis. If the surgical procedure is successful and the prosthesis correctly fixed, without any infection of the tissue surrounding the device, then the long term wear and instability of the acetabular component would be the probable cause of failure.

Since the first successful attempts to replace diseased joints with prostheses, many scientists struggled to find ways of prolonging their life. As it is well known, the wear of UHMWPE (ultra high molecular weight polyethylene) and the resulting debris are the primary causes of long time hip implant failure.

The wear debris produced in the joint capsule can have two major effects on the long term function of the prostheses. First, if the wear of the polymer allows the metal or ceramic femoral head to penetrate into the acetabular cup, then the neck of the femoral component can impinge on the rim of the acetabular cup leading to joint luxation. Second, the polymer wear debris is released into the tissue, triggering a foreign body reaction. The macrophage cells engulf the polymer particles resulted from worn surface and these activated macrophages stimulate cellular reactions, leading to osteolysis (loss of the bony tissue) and consequently prosthesis loosening.

The finite element method (FEM) has become the method of choice to analyze the mechanical behavior of objects characterized

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Nomenclature

A	matrix containing influence coefficients
A_i	contact surface of ring i
a_n	Fourier coefficient
B	vector containing distances between bearing surfaces under no load condition
b_n	Fourier coefficient
c_n	Fourier coefficient
c_{ij}	influence coefficients
D	inner diameter of the acetabular cup
d	diameter of the femoral head
d_n	Fourier coefficient
d_x	distance from a point on the bearing surface to the head axis of rotation
ds_a	infinitesimal sliding distance
E	modulus of elasticity
F	hip joint loading
G	shear elasticity modulus
h	femoral head displacement
K	elliptic integral of the second kind
k	index of the gait
M	Torque
n	number of terms in the Fourier series expansion
p	contact pressure
p_{ae}	specific load (relative Stribeck pressure)
r	spherical coordinate (radial distance)
r_c	contact radius
r_h	radius of the femoral head
r_i	radius of ring i
R_w	cavity radius in worn zone
R_u	cavity radius in unworn zone
r_{cr}	critical contact radius
T	period of the gait cycle
t	time
w	displacement of the bearing surface
W_B	body weight of the patient
X	vector containing the contact pressures and head displacement
z	distances between bearing surfaces under no load condition
α	inclination angle of the loading force relative to the vertical axis
β	angle of the acetabular cup axis relative to the horizontal plane
χ	internal rotation angle
δ	half width of a ring
ϵ	admissible error
η	abduction–adduction angle
γ	characteristic angle of the first cylinder
μ	friction coefficient
ν	Poisson coefficient
ω	angle between load direction and head rotation axis
ψ	relative clearance
ψ_0	initial relative clearance
ψ_e	equivalent worn joint relative clearance
ρ	radius of applied concentrated force
τ	tangential stress
τ_0	shear stress necessary to start the sliding motion
θ	spherical coordinate (polar angle)
θ_c	angle of contact
θ_{cr}	critical contact angle
φ	spherical coordinate (azimuthal angle)
ξ	flexion-extension angle

by complicated shapes and which are subjected to complex loading. As such, it is widely used in the study of contact between solids [10–13]. Unfortunately, the use of FEM software for contact problems involves large computational power and time, and the use of several varying model parameters proves to be cumbersome.

The scientific literature contains a lot of papers on wear prediction of hip joint prostheses. Mattei [2] made a review of the main lubrication and wear models of hip implants, underlining the distinction between models for *soft-on-hard* and *hard-on-hard* bearing couples. Recently, many authors developed wear models based on the so-called *cross-shear* effect [14–19]. Kang [16] studied the effect of cross-shear on the wear of UHMWPE in a multidirectional pin-on-plate machine. Several studies have suggested that cross-shear has an important effect on UHMWPE wear rate. Dressler [18] found in a recent study that the wear of UHMWPE increases proportionally with the number of cross-shear events and that the wear rate immediately after a change in direction is high, while for continued rectilinear sliding the wear rate drops.

In a previous study, Kang [17] found that for large femoral head sizes, increased wear volumes were obtained as a result of longer sliding distances and reduced contact pressure. Buford and Goswami [20] concluded in their paper that wear of hip implants is a function of several variables like: contact stress, lubricants, and clearance. They also found that higher contact stresses result in lower friction and decreasing wear rates.

Another factor influencing the wear rate of hip implants is the bearing surface roughness. Wang et al. [21] studied the influence of femoral head roughness on the wear of UHMWPE cups. A direct liaison between head roughness and wear rate was found, but the dependency was much weaker the expected.

It is to be mentioned that, for simplicity, the authors of this work decided not to employ the cross-shear effect, the effect of femoral head roughness or the existence of a lubricant between the articulating surfaces. Further work is needed to improve the current model by including the effect of cross-shear, surface roughness, and the presence of a lubricant.

This paper presents a parametric numerical model based on general elasticity theory. This model offers the possibility to determine the pressure contact as a function of mechanical properties of the natural and artificial materials, normal and tangential loads, and geometry of joint components [22].

The aim of this paper is to analyze the effect of clearance between the two articulating surfaces on the pressure contact and wear of hip prostheses. The main reason for developing a numerical model for calculation of the contact pressure distribution for hip joint prostheses is that the Hertzian theory of contact is not applicable for conformal contacts and the FEM analyses require large computational effort and is difficult to parameterize.

2. The numerical model

2.1. Forces acting on the prosthesis

Joint reaction force profiles for level walking and running were adopted from the literature [8,23,24]. The force components and the acetabular cup orientation were defined relative to a Cartesian coordinate system fixed to the pelvis and having the origin in the cup center of symmetry and the three axes (x,y,z) pointing