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Abstract

The synovial joint has two main components: solid one represented by the cartilage, and bio-fluid - by the synovial fluid. The cartilage is a soft anisotropic solid containing pores filled with a fluid. In this paper is determined the pressure distributions in a thin layer of non-Newtonian, lubricant inside the deformable gap of spherical human hip joint. The load carrying capacities in human joints with cartilage deformations are much smaller than that obtained for not deformable cartilage surface.

The changes of the joint gap height during the lubrication process are caused by the deformation of two cooperating spherical joint surfaces covered by the soft cartilage superficial layer. Hypo-elastic deformations of cartilage are taken into account. In the general case the cartilage can be subjected to large deformations.

The main results described in this paper are as follows:

1. *Numerical calculated values of pressure distributions for the elbow cylindrical human joints performed in this paper by virtue of analytical models taking into account the effects of congenial and growth influences on the lubrication process are compared with initial measured hydrodynamic pressure values performed by means of AFM. Measured pressure values obtained by the S. Chizhik et al. 2006 in experimental way, are different about 7 percent from the numerical values obtained in presented paper using the analytical solutions.*
2. *In presented paper is derived the modified Reynolds equation containing the terms describing the influences of congenial and genetic properties of the lubricant and micro-bearing materials on the pressure and load carrying capacity of bio-joints and micro-bearing.*

The comparisons presented in this project between human bio-joints and micro-bearings are indicated that the biobearing theory of lubrication is very helpful in MEMS and NEMS devices.

The research presented in the project provides an important impact for developing the new scientific domain such as cyto-tribology, histo-tribology or tribology of cells, and tissue and of micro-surfaces occurring in mechanical micro-bearings.

According to the participants knowledge such scientific domains are completely new and have been not so far initiated by any scientific centre and in any area of tribology and tissue engineering.

Keywords: *hydrodynamic pressure, hyper-elastic human joints, deformable gap*

1. Principles of the lubrication of journal bearing and human joint with non-Newtonian lubricants in the magnetic field

Paper [1] is presenting the principles of slide journal bearings and human joint lubrication with non-Newtonian lubricants or liquids.

This fundamental considerations are designed to be implemented in the field of non-conventional systems for human bio-bearing lubrication by pathological or improved non-Newtonian synovial fluid with viscoelastic and micropolar properties in variable time-dependent magnetic induction field, for deformed bone viscoelastic surfaces and hyper-elastic cartilage surfaces of human joints under random unsteady conditions.

2. Basic equations for the ferrofluid flow in bearing and in human joint gap

In paper [2] basic equations for the ferrofluid flow in machinery slide journal bearing, as well as in various human hip joint have been derived. Time-variable impulses of magnetic induction field have been applied during magneto-therapy cure ill synovial liquid by increasing its viscosity. One way of generating a magnetic field in human joint gap is to inject a bio-tolerable ferrofluid into the gap.

The ferrofluid are a colloidal mixture of a dissipating (basic) agent and dissipated one (magnetic particles). Usually, ferric oxide Fe_3O_4 or gadolinium oxide is used as a dissipated agent. Water, synovial liquid, hydrocarbons, esters, fluoroderivatives of hydrocarbons and organic fetes are applied as a dissipating agent. In one cubic millimeter of ferrofluid contains about 10^{15} magnetic particles of 5 to 15 nanometers in size [2]. Ferrofluid viscosity may be controlled by means of an external magnetic field. Such bio-tolerable ferrofluid for medical purposes is manufactured by HEART GmbH in Berlin. Ferrofluid can be inserted in the form of microcapsules which, after injection to joint gap, disintegrate to emit magnetic particles (ferric oxides) of a few to a dozen or so nanometers in size. The dissipated agent makes Brown's motions in ferrofluid that prevents the particles against clustering and increases their dissipation. The magnetic particles are covered by a surface active agent in the form of long chains of molecules or an electrostatic layer. This prevents clustering the magnetic particles when the external magnetic field is cut off. In the moment when the magnetic field is active a change in ferrofluid viscosity is obtained due to two phenomena. The first of them is the clustering of magnetic particles into chains which increases resistance of flow. The second is rotational motion of magnetic particles resulting from action of magnetic and mechanical forces [2].

3. Basic equations for the elastic and hyper-elastic cartilage located on the acetabulum

In papers [4] experimental properties of the elastic and hyperelastic cartilage resting on the bone head and acetabulum in human joints have been presented. It includes also the properties of bearing alloy resting on the cooperating surfaces in endoprosthesis. Non classical equations for determining the elastic and hyper-elastic displacements have been derived, too.

4. Conjugate fields in the thin layer problems occurring in human joint lubrication

In papers [2] and [3] conjugate fields in the thin layer problems occurring in human joint lubrication and mechanical slide journal bearing lubrication during the stationary and unstationary motions have been presented.

These papers include calculations of carrying capacity for synovial unsymmetrical fluid flow in deformed human joint gap, especially in the hip joint. The following assumptions are taken into account: the synovial fluid flow is stationary, isothermal and unsymmetric and the fluid is compressible in a time-variable magnetic field; bone head has a rotational motion, synovial fluid in human joint gap can be squeezed; this non-Newtonian synovial fluid has a varying viscosity with changeable and deformed gap height in human joint, and finally the density of synovial fluid is constant. The simplified system of basic equations for pressure and synovial fluid velocity distribution, have been analysed. The numerical and analytical formulae for capacity force with taking into account conjugate fields of the stresses and deformations occurring in elastic cartilage and in synovial fluid have been obtained by application of theory of elasticity and fluid mechanics. It can be considered as the novelty of this section. The obtained analytical solutions for values of capacity forces make numerical calculations easy, which may be very useful in the case of medical diagnosis.

5. Ferrofluid flow occurring in the thin layers using curvilinear coordinates

In paper [4] the main principles of ferrofluid flow in thin layer between two cooperating surfaces have been delivered. Today, different magnetic induction fields have been used in the modern therapy process of various illnesses of human joints. The thin layer of the synovial fluid separates two co-operating bone surfaces in human joint. The consideration of hydrodynamic lubrication problems and lubrication in magnetic induction field requires to take into consideration also the actual various geometries of human joint surfaces. Centrifugal forces and slow - variable changes of the magnetic induction field are taken into account. To solve this problem it is necessary to apply the proper coordinates and to know their Lamé coefficients corresponding to the various geometries of human joints. In this section formulae for Lamé coefficients describing gap geometry of various joints have been given. For instance, using the spherical or elliptical coordinates are the best way for describing of the human hip joint geometry. The parabolic and hyperbolic coordinates are optimal tools for describing the human elbow or phalanx joint. In order to study the synovial fluid flow in human joint gap, fluid velocity components and appropriate Reynolds equations to determine hydrodynamic pressure distributions in magnetic induction field for various gap geometries have been derived in this section.

6. Boundary layer simplifications for hydrodynamic problems, theory of elasticity and Maxwell equations

Boundary layer simplifications for hydrodynamic problems, theory of elasticity and Maxwell equations have been described in paper [5]. In contrast to papers delivered by Batchelor, Hayes, Maurel, Mow, the present elaboration shows an unified and analytical method of solutions of the lubrication problem in human joint gap for various joints, e.g. those with spherical, parabolic, hyperbolic bone surfaces and for non-Newtonian micropolar experimental properties of synovial fluid.

7. Analytical and numerical solutions for calculation of velocity, pressure, capacity and temperature of viscoelastic, laminar, stationary and unsteady lubricant flow in deformed biobearing gap of human joints

In papers [2] and [5] analytical and numerical solutions for calculation of velocity, pressure, capacity and temperature of viscoelastic, laminar, stationary and unsteady lubricant flow in deformed biobearing gap of human joints have been presented. The theorem and formulations which describe the unification of analytical and numerical methods of partial differential non-linear equations for axial-symmetrical and unsymmetrical flow of synovial fluid in human joint gap have been given, too.

8. Analytical and numerical solutions for calculation of frictional forces, friction coefficient induced by viscoelastic, laminar, stationary and unsteady lubricant flow in deformed biobearing gap in human joints and random variable joint surfaces

In papers [3] and [5] analytical and numerical solutions for calculation of frictional forces, friction coefficient and wear induced by viscoelastic, laminar, stationary and unsteady lubricant flow in deformed biobearing gap in human joints and random variable joint surfaces have been elaborated. In these papers, an original numerical solution regarding unsymmetrical viscoelastic hydrodynamic lubrication of human joints with synovial fluid with periodical variation in time and under unsteady magnetic field have been delivered.

It is assumed that bone head in human joint moves in two directions, namely in circumferential and meridional directions. It is also considered that bone head can make rotational motion in two directions at two various angular velocities. Basic equations describing the flow of synovial fluid in human hip joint are solved both analytically and numerically.

Numerical calculations are performed using Mathcad 12 Professional, and by implementation of finite difference method. This method satisfies stability of numerical solutions for partial differential equations and therefore the values of capacity forces occurring in human joint.

The solutions are given taking into account the flow of viscoelastic synovial fluid as rotational, periodic and unsteady; gap height as a periodic time-dependent function, viscosity of synovial fluid and geometry of gap height as variable, density of synovial fluid as constant, and last but not least synovial fluid in magnetic field as isothermal and incompressible flow.

9. Analytical and numerical calculation of velocity, pressure, capacity and temperature for viscoelastic, turbulent, unsteady lubricant flow in deformed bio-bearing gap with described roughness of human joints by stochastic variables

In chapters 7.1, 8.1, 8.2 and 8.3 of the monograph [7], as well as in papers [8], [16] and [19] analytical and numerical solutions for calculation of velocity, pressure, capacity, temperature in human joint gap during unsteady lubrication with viscoelastic liquid and for random conditions have been prepared, in which the surface roughness of cartilage, has been considered. The concept of analytical and numerical calculations of pressure and capacity during hydrodynamic lubrication of human hip joint surfaces in unsteady motion have been delivered. It is assumed that spherical bone head in human hip joint moves at least in two directions: circumferential and meridional. Basic equations describing synovial fluid flow in human hip joint are solved both in the analytical and numerical way. The numerical calculations are performed in Mathcad 12 Professional, using finite differences method. This method satisfies stability conditions of numerical solutions of partial differential equations and gives real values of fluid velocity components and friction forces occurred in human hip joints.

The turbulent lubrication of human joint surfaces rather rarely occurs because of small values of relative velocities of the bone head and, all the more, of cartilage. However the turbulent lubrication of synovial liquid through joint gap may occur in emergency events of the narrowing of joint gap associated with osteoarthritis, as well as in the case of very quick motions of limbs associated with sport activity. Size description of joint gap depends not only on the system coordinates and time but also on dimensionless random variations of thickness of synovial liquid layer. The thickness variations are often caused by random loads applied to the joint as well as randomly variable roughness protrusions of cooperating surfaces, measured from an assumed height level.

10. Analytical and numerical solutions of friction forces, friction coefficients and wear for unsteady periodic and impulsive motion with various frequencies and amplitudes and for unsteady lubricant flow in deformed bearings gap

In chapters 8.4 and 8.5 of the monograph [7] and also in papers [9], [10], [11], [12], [13], [14], [15], [17], [18], [19], [22] and [23] analytical and numerical solutions for calculation of velocity, pressure, capacity, friction forces, friction coefficients and wear in human joint gap during unsteady impulsive and periodic lubrication with various frequencies and amplitudes in the case of two deformed, permeable cooperating surfaces of cartilage in human hip joints have been presented. The measurement of the cartilage roughness of the cartilage surfaces using the mechanical and laser sensors, as well as Atomic Force Microscope have been described. Additionally, measurement of friction forces in micro level has been explained.

A rough and used cartilage surface in human hip joint suddenly changes its lubrication parameters after injury. Stochastic changes of roughness of bone head surfaces and stochastic changes of the load imply random changes of gap height. Hence, pressure distributions and capacity, as well as friction forces and friction coefficients radically decrease or increase in values during several microseconds after the trauma. These changes are very difficult to be measured, hence to perform an appropriate numerical research in this field is very important. To obtain the right numerical results it is necessary to perform the calculations using stochastic description with optimum standard deviations. Synovial hip joint represents so sophisticated bearing system that even novel technology cannot fully replicate it. Synovial hip joint utilizes sliding between smooth spherical surfaces to enable a limb to be rotated, while carrying a time-dependent load in various directions. The chapter 8 of the monograph [7] presents the concept of analytical and numerical calculations of pressure and capacity for hydrodynamic non-isothermal lubrication of human hip joint gap in unsteady periodic motion. It is assumed that human hip joint moves with rotational motion in two directions namely in circumferential and meridional. Spherical bone head rotates with rotational motion in two directions at two various angular velocities. The papers: [14], [15], [17], [18], [19], [22] and [23] explain the friction forces in various human joint with various geometry of bone co-operating surfaces and variable joint gap height for unsymmetrical flow of synovial fluid.

11. Analytical and numerical solutions for calculation of velocity, pressure, capacity and temperature for micropolar laminar stationary and unsteady oil flow

Periodic motion with various frequencies of bone head and acetabulum of human hip joint has not been hitherto considered in the foregoing papers. In these papers the viscoelastic lubrication under random conditions has not been taken into account.

The novelty of the sections: 8.4, 8.5, 8.6 of the monograph [7] is carrying out of capacity calculations of human hip joint for roughness of bone and cartilage surfaces and considering the micro or nano-bearings lubricated through a periodic flow with various frequencies and amplitudes. The monograph [7] and papers [24], [25], [26], [27], [28], [29], [30], [31], [32] and [33] present analytical and numerical solutions, giving the experimental data for friction forces and friction coefficients in mechanical slide journal micro-bearing, as well as in human joints or bioreactors.

In papers [24] - [33] analytical and numerical solutions for calculation of velocity, pressure, capacity, friction forces and friction coefficients in human joint gap and micro or nano-bearing during stationary and unsteady lubrication of synovial incompressible non-Newtonian or micropolar synovial fluid flow in deformed joint gap have been presented.

12. Analytical and numerical solutions for calculation of friction forces, friction coefficients and wear for micropolar laminar stationary and unsteady oil flow

The monograph and papers [24-33] present the results of calculation of friction coefficient and wear for non-Newtonian or micropolar laminar stationary, unsteady oil flow in micro-bearing gap and in gap of human joints.

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