INTELLIGENT ARTIFICIAL JOINT AND REGENERATION PROBLEMS IN ARTICULAR JOINTS

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Abstract

Taking into account the increasing need to artificial joints for in-vitro use, this paper presents a layout of a challenge leading to detail analyzing of regeneration problems of articular joint and gives a step-by-step plan for designing a novel intelligent artificial joint. This paper has been prepared based on the objective of European Project MTKD-CT-2004-517226 to represent the methodology and goal of the idea described in and make possible wider discussion on this subject for further developments during the realization.

1. Reason of research

Gdansk University of Technology, as the coordinator, in cooperation with other European universities: Graz University of Technology, Clinic of Orthopaedic and Traumatology Silesian Medical Academy in Sosnowiec, Clinic for Orthopaedics and Sportorthopaedics of the Tech. University Munich, University of Applied Sciences, Giessen-Friedberg, Institute for Fluid Mechanics, University of Karlsruhe and Central Institute for Biomedical Engineering, University of Ulm submitted a ToK proposal to the European Commission on May 2004 which was entitled "Bio and Slide Bearings, their Lubrication by Non-Newtonian Oils and Application in Non-Conventional Systems". The proposal was submitted under Sixth Framework Programme, with Call Identifier: FP6-2003-No.517226, and finally is accepted as the Contract MTKD-CT-2004-517226. The proposal after negotiation is confirmed to financing from 2005 to 2008 due to high-level marks for scientific, technological, socio-economic and European impact issues, as well as management aspects.

The World Health Organization (WHO) has declared the present decade the bone and joint decade. In 1988 in USA the estimated total cost of osteoarthrosis was $54.6 billion. Annually in Germany more than 30 million medical treatments and more than 50 million days of temporary or permanent disablement, are due to the diseases of cartilage and bone. It is not surprising that the number of human joint diseases shows an exponential increase over the last years in Europe. In last ten years in European Union the number of bone fractures caused by the osteoarthritis increased twofold. More than 100000 total hip or knee joints are implanted during one year in Germany. Within ten years 5% of them fail by aseptic loosening.

It can be estimated that yearly 2.5 million joint fractures occur worldwide. Only in 2000 in EU 414000 joint fractures was recorded. The increase in number of joint fractures in EU, anticipated on the ground of demographic development in the next 50 years, would reach about one million.

2. State of knowledge

The tissue articular joint regeneration and engineering of cartilage implants may open a new path for the surgical treatment of joint surface defect. Autologous chondrocyte transplantation has been gaining in clinical significance over the last several years. The cartilage engineering of cartilage implants of human joints is of a great importance for treatments - by transplantation - of various cartilage diseases. The project is also addressed to such social objectives as quality of life, human health and professional safety. Intrinsic mechanism of cartilage regeneration and cartilage repair will be also investigated in the proposed project.

The articular cartilage occurring in human articular joints is considered a tissue without the capacity to repair, thus mechanical wear of tissue joint is often designated as a normal tribute to increasing age [1], [2], [3].

A lot of investigators prefer the statement that cartilage has no spontaneous capacity to repair or to regenerate, however, some researchers observed that cartilage has some potential to refill the defect by a passive cartilage flow starting from the edge of the defect. The still increasing variety of therapeutic methods is fascinating but none of these techniques have been able to restore the damaged cartilage so far. Therefore the regeneration of articular joint seems to be a promising way to support development of the medical treatment methods in the area in question.

There is another strong reason speaking for the necessity of cartilage repair to obtain new cells of cooperating joint surfaces for the efficient treatment of bone head diseases in human joints. Treatment of traumatic or degenerative defects of articular cartilage is well known for surgeons. Different diseases of cartilage can be distinguished. All of them have an individual cause and an individual progress. However better and better understanding the physiology and pathophysiology of cartilage diseases creates new forms of treatment and leads to the development of new therapeutic approaches and techniques which demand regeneration of human joint cartilage to be further developed and improved.

One of the major result of the proposed research is the computational model of friction forces i.e. viscous shear stresses due to the gradient in velocity profile at the synovial fluid-cartilage interface, which makes it possible to simulate and determine the regeneration process of cartilage as well as to control operation and optimize friction forces occurring on the cartilage surface during the joint lubrication. Frictional drag as the viscous fluid flows through the porous matrix of the tissue is considered.

Therefore, an interdisciplinary, multi-stage, analytical, numerical and experimental measure is needed to correct the current lack of knowledge and technology of cartilage regeneration. The ultimate goal would be developing a prototype of intelligent artificial and articular hip joint. This paper should be treated as layout of such a challenge. The objective of this challenge should be modelling, simulation, control and optimization of the cartilage properties, leading to elaboration of the prototype of an intelligent artificial joint by using advanced optimization algorithms.

In this regard, two main outputs should be worked out.

New generation of biological synovial fluid by applying the ferrofluid additions and a new method of lubrication and simultaneous control of the synovial liquid behaviour using the viscosity control method.

An intelligent artificial joint which can “remember” the process of cartilage (tissue) behaviour for “learning” and implementation of optimum control system based on the created knowledge-base by applying the neuro-fuzzy methodology [4]. The idea of “intelligent artificial joint” should be treated not only as a mechanical-biological process, but also as a process which improves the quality of extracted biomaterial.

3. Research deficiency and what should be done

The application of theoretical and computational model for representing the behaviour of cartilage in human joints under unsteady hydrodynamic conditions of synovial fluid flow has not examined so far. Scientific efforts of the proposed challenge shall contribute to improvement of this process by delivering the hydrodynamic flow characteristics of the considered media, with the use of CFD tools. Up to now, only some parameters of cartilage remodelling process are kept under control (temperature, external and internal pressure values and rate of flow). Such cartilage conditions are very simplified and they hardly reflect real state of work of human joints. The control aspects of cartilage regenerations should be improved. A study of the multifunctional cartilage remodelling in vivo and in vitro under hydrodynamic, unsteady, viscoelastic, non-Newtonian flow of nutrient fluid in the thin layer around the cartilage surface by using stochastic methods and neural network tools is necessary. Moreover, the engineering support for cartilage development during the remodelling is to be delivered.

In this regard, it is necessary to describe the hydrodynamic parameters during the flow of non-Newtonian biological liquids and perfusion process of cartilage in joint gap during the lubrication. Perfusion of cells of tissue by the nutrition liquids and other biologically tolerable media with oxygen carrying fluorocarbons have to be considered with taking into account the cooperating joint surfaces during the lubrication process.

A computational model accompanied by simulation and determination of friction forces in the lubrication process should be elaborated. Such a computational model should consist two parts. Flow of non-Newtonian synovial media including a certain percentage of oxygen carrying emulsions of Perfluorocarbons (PFC) should be calculated as a viscoelastic fluid flow. Apparent dynamic viscosity depends on the components of strain tensor. Liquid velocity components and pressure values are to be determined, calculated and simulated. Simplifications of the boundary layer would be made for local flows [5], [6], [7], [8].

Having such a model, it can be applied for obtaining analytical and numerical results for various shapes of cartilage structures and various shapes of porous channels inside the cartilage by using random variables and stochastic approach to rough surface of cartilage sample. Time dependent fluid velocity components during the perfusion, speed of tissue growth, and friction forces during the time of lubrication have to be numerically examined and investigated. Making the model enables one to design and synthesize the related control system and to optimize proper friction forces occurring on the cartilage surface. The simulation results have to be verified by experimental and clinical tests. An appropriate control principle, adequate control strategy and algorithm of optimization should be delivered, too. The control theory can be applied to design an optimum regulator. This optimally controlled system will be supported then by a database elaborated during simulation and experiments. The database will be the core of a further developed knowledge-based system which employs the neural networks and fuzzy logic theory to improve characteristics of the intelligent bioreactor.

A certain relationship between flow rate of the synovial fluid supplied into joint gap, and velocity of the flow around the cartilage, friction forces generated by the flow, on the other hand, should be determined. Not only quantity of the flow rate of supplied fluid influences the cartilage regeneration, but also direction of the flow velocity of supplied fluid and dynamic conditions of movable bone head affect on. The flow rate of supplied fluid is intensified by the increases of the dynamic viscosity of the synovial fluid. Real relationships for the above mentioned dependencies would be determined. Moreover, the influence of weeping or suction velocity effects (~100μm/s) of the cartilage surface during the lubrication process has to be indicated. Friction force occurring in the cartilage surface increases if flow rate and fluid dynamic viscosity increases, too. Viscous shear stress increases in such an interval from 0.005 Pa to 0.055 Pa and retains almost proportionally for flow rate increases from 0.6 to 3.0 ml/min. Therefore the proposed challenge is addressing nano-technology, as well as new production processes and devices.

4. Goal definition and to whom is it addressed

The social and ethical impacts of such a challenge are given through the following goals: 1) improving the quality of life: by increasing the success rate, as well as possible number of transplantations (~25%), 2) social impact: by enhancing the ability to recovery of patients suffering the problems with joints (~20%). The second order goal is financial impact by time and cost saving (~10% and ~20%, respectively).

Medical clinics as end-users, biological, biomaterials and biomechanical research parties, as well as computational fluid mechanics and control system researchers are three main groups that the challenge is addressed too.

5. Research areas

The objectives of the proposed challenge are mainly related to nanotechnologies and nanosciences, knowledge-based functional materials, as well as new production processes and devices, but particularly intelligent cartilage repair and regeneration should be considered. In details, it addresses the following research domains:

5.1. Technologies associated with the cartilage regeneration and repair and processing of knowledge-based multifunctional transplanted tissue:

- *Multifunctional Biomaterial*

  Intelligent artificial and articular joint requires utilization of radically innovative technologies and can lead to enormous benefits caused by the multifunctional lubrication. The proposed topic will focus on technological novelties and methods applied during the lubrication with relation to chemical and physical processes. To the innovative technologies are numbered a new biological fluid with ferrofluid additions and a new method of lubrication and simultaneous control of the friction forces. On their ground a new cartilage with better capacity to repair and regeneration and a new cartilage with higher hardness and durability and lower friction coefficient, can be obtained.
- *Cell Surface*

  A new achievement of this project is accounting for the very thin multifunctional layer of the synovial fluid near the tissue surface, produced after the new technology of lubrication. The multifunctional thin layer which arises in surrounding of the cartilage surface during a new method of lubrication is of great importance for the proper behaviour of cartilage. The thickness of such film amounts from 10 to 100 nm. In such very thin layer boundary lubrication of the cartilage surface occurs because the velocity of the fluid particles simultaneously attains the value of about 100 nm/s. Such thin film has a radically new nanostructure with chemical and physical properties that significantly differ from those of conventional perfusion occurring in classical technologies.
- *Tribology of Biomaterials*

  The thin boundary layer of the biological fluid (produced by virtue of new technologies) cooperates with the thin superficial layer of cartilage laying on the cooperating joint surfaces. These mutual tribological influences make it possible to obtain a greater strength and durability of joint surfaces.
- *Intelligent Biomaterials*

  The intelligent synovial fluid contains enzymes, microcapsules with magnetic nano-particles that have specific active behaviour and also improve the incorporation of substances providing the superficial layer of cartilage with desired functionalities.

5.2. Engineering support for cartilage

- *Nanoparticles in Biomaterials*

  The magnetic nano-particles are novel multifunctional materials of wide applications. The magnetic nano-particles introduced at first into thin fluid layer and further into superficial layer of cartilage have two important aspects: miniaturisation - to include at least two functions in a small volume, and hybridisation - to gain from associating inorganic and organic components. Magnetic induction field in nano-scale at first improves lubrication and later increases the dynamic viscosity of synovial fluid and increases human joint capacity after regeneration.
- *Nanointeraction of Biomaterials*

  The interaction of particles released from the articulating surfaces of azetabulum and bone head of implanted artificial joints and the surrounding tissue is one of the major reasons for the proposed investigations. Hence the engineering support during the cultivation of the proper tissue in bioreactor to gain a good tribological cooperation with artificial implants is necessary.

  We take into account the nanostructure additives materials in which the intimate internal structure or constituents and material coefficients can be modulated for application to obtain optimal properties in contacting surface regions in artificial hip joint heads. Are determined mechanical coefficients for hyperplasic, anisotropic, viscoelastic materials.

5.3.Tribology-related surface engineering for multifunctional materials

- Extending the performance and functionalities of multifunctional biomaterials by ambitious knowledge-based engineering of their surface.
- Biomaterials surface treatment dealing with multi-functional biomaterial durability and efficiency.

6. Innovations and new knowledge

As it was mentioned before, the proposed research determines a certain relationship between flow rate of the synovial supplied into joint gap on one hand, and velocity of the flow around the cartilage, friction forces generated by the flow, on the other hand [9], [10], [11] (see Fig. 1). It can be proved that not only quantity of the flow rate of supplied synovial fluid has influence on the proper lubrication effects, but also direction of the flow velocity of supplied synovial fluid and dynamic conditions of movable bone head. The flow rate of supplied synovial fluid is intensified by the increases of the dynamic viscosity of the fluid. Real relationships for the above mentioned dependencies would be determined. Moreover, the influence of weeping or suction velocity effects (100μm/s) of the cartilage surface on the proper lubrication and least wear will be indicated. Friction force occurring in the cartilage surface increases if flow rate and fluid dynamic viscosity increases. Viscous shear stress increases in the interval from 0.005 Pa to 0.055 Pa and retains almost proportionally for flow rate increases from 0,6 to 3.0 ml/min [12], [13]. The innovation and expected new knowledge are as follows:

The elaborated algorithm of derived formulae makes it possible to indicate optimum values of flow rate of supplied synovial liquid to obtain optimum growth of tissue.

Providing analytical solutions of synovial motion equations for unsteady flow of viscoelastic liquid in the thin layer during lubrication enables to obtain optimum shear stresses induced in the fluid and in superficial layer of cartilage during the lubrication process.

The artificial neural network makes it possible to simulate and control of lubrication process Fig. 2. It was observed that magnetic induction field supports the joint capacities and repair process.

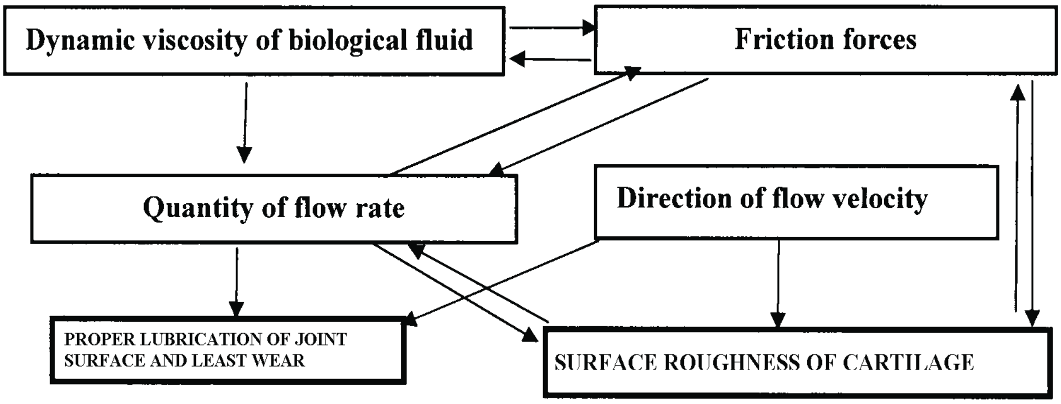

Fig.1 Logical scheme

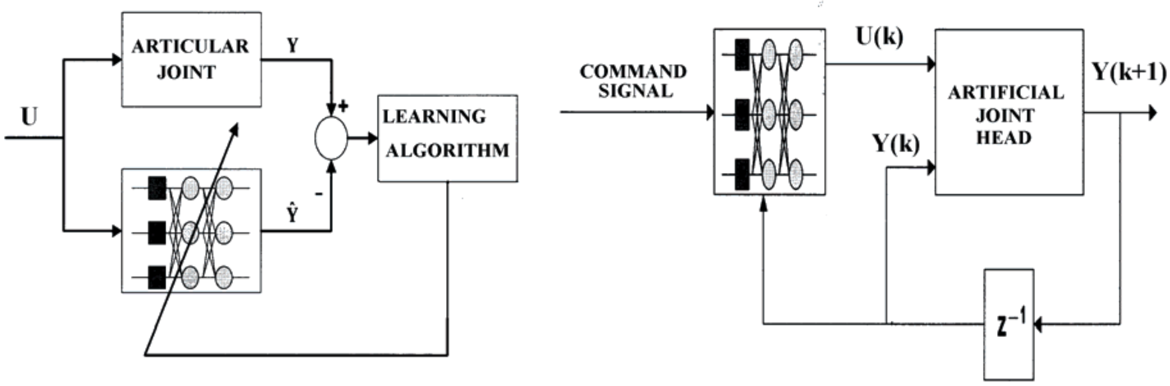

Fig. 2. Structure of articular joint identification and Inverse Control Strategy for Artificial Joint Head, U-input vector, Y-output vector

7. The map of further research

The research, technological, development and innovation activities in human joints lubrication are mainly related to investigation on the following items:

- Approaches related to clinical, technical and standards in connection to end-users requirements based on experience on patients.
- Synovial fluid characteristics and new generation of biological fluids using ferromagnetic additives and viscosity control.
- Cell and cartilage characteristics in superficial layer of cartilage.
- Methods and instruments for measuring the transplanted cartilage in human joints and friction forces characteristics.
- Software tool including data extracted from the measuring of transplanted cartilage and synovial fluid variables and wear, as well as their analysis.
- Mathematical models and simulation results of friction forces and wear determination.
- Optimum regime and condition for synovial fluid flow in hip joint gap.
- Software tool for simulation, synthesizing and optimisation of synovial fluid flow control system.
- Concept of intelligent artificial joint and integrated related software.
- Data and knowledge base of lubrication parameters.

Table 1. Map of activities

Stage	Sub-goal	Novel features
I. Acquiring the necessary data on biophysical, geometrical, structural and mechanical properties of human joint elements	- Realistic characteristics of periodic and impulsive loads and motions of human joints and their cartilage surfaces - Realistic hydrodynamic parameters of synovial and other biological liquids	- Statistical and stochastic description of loads on joints - More exact definition of parameters of liquid with taking into account a.o. specific friction phenomena
II. Mathematical modelling: Differential and difference analysis, variations analysis, probability and stochastic description, set theory and topological methods of solutions	- Mathematical description of hydrodynamic unsteady phenomena occurring in human joints. - Computer programs for numerical calculations. - Numerical analyses of the flow phenomena of synovial fluid. - Description of results in terms of artificial neural networks.	Accounting for: - Friction forces in the thin layer of non-Newtonian liquids close to tissue surface - 3D geometry of joints. - Roughness of cartilage surfaces in stochastic conditions - Description of squeeze- suction flow of synovial fluid inside the bearing gap. - Influence of magnetic induction field on the lubrication parameters.
III. Mathematical simulations	- Mathematical simulation of hydrodynamic flow phenomena around the cartilage surface in joint gap based on analytical and numerical calculations	- Performances based on differential and difference calculations and on neural networks, genetic algorithms and fuzzy logic tools
IV The methods of numerical calculations of non-linear hydrodynamic differential equations and their active control in thin boundary deformable layer near to the cooperating hyperelastic deformable surfaces	- Isothermal, laminar unsteady and turbulent flow of synovial fluid in curvilinear coordinates inside the various joint gaps.	-Hyperelastic deformable cartilage surfaces - Active control of vibrations with various frequencies and amplitudes inside and between the boundary fluid layer and superficial layer of cooperating deformable surfaces in biobearings
V. Optimization and control	- Optimization of the structural and metabolic properties of engineered cartilage. - Optimization of the mass transfer and hydrodynamic effects associated with dynamic flow properties	Making it possible to optimize operational conditions of a artificial joint, reflecting optimum conditions for friction forces, friction coefficient and wear
VI. Design of intelligent artificial joint	- Design of an intelligent artificial and articular joint - Possibility of cultivation of autologous chondrocytes	- Intelligent = possible to be fully controlled in operation at optimum working conditions using a knowledge base and remembering the history to learn from
VII. Building of prototype of artificial joint	- Physical model of the designed artificial joint	- Rotational artificial joint

- Application of neuro-fuzzy methodology for intelligent artificial and articular joint.
- Design of intelligent artificial joint.
- Manufacturing the prototype of intelligent artificial joint.
- Risk and comparative analyses.

Table 1 shows the map of activities should be taken into account to achieve the ultimate goals of the proposed challenge.

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