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Biophysical and biotribological aspects of joints functioning and medicamental correction

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ABSTRACT

Modern trends in joint biotribology are presented. The extent of the achievements in this field at the turn of the 21st century is discussed. This period is distinguished by the discovery of liquid-crystalline and quasi-electret states in synovial liquids; ascertainment by AFM of new boundary lubrication mechanisms in joints, which are realized at the nanolevel; and development of methods for in vitro study of friction in joints using electromagnetic fields able to simulate the natural articular biofield. A relationship is shown between biotribology and the chief directions in contemporary orthopedics including: intraarticular chondroprotection exercised via local therapeutic methods based on tribological monitoring of pharmaceutic substances; injection of drugs based on blood serum; and development of a new generation of articular endoprostheses able to simulate the biophysical properties of synovial joints. It is shown that progress in modern biotribology has provided scientific substantiation of orthopedic treatment procedures.

1. Introduction

A human joint is a natural frictional pair that ensures locomotor activity in the course of man's life. Healthy joints are enclosed tightly in a capsule of conjunctive tissue. Their friction is extremely low and the wear of their movably contacting layers in the hyaline (vitreous) cartilage is compensated. We can justifiably attribute to biotribology the discovery of the effect of abnormally low friction in cartilages separated by a synovial layer in the liquid-crystalline state [1]; the quasi-electret state of the lubricating synovial film [2]; the effect of man's biophysical field on lubrication in joints [3], and many other findings. The dominant task of biotribology is to render scientific support to orthopedics, which is a branch of clinical medicine involving the study of congenital and acquired deformations and dysfunctions of the locomotor system, and the development of methods of their prevention and treatment [4].

In 2000, General Director of the World Health Organization Harlem Brundtland announced the beginning of the world-wide decade of bone and joint diseases. This decennial campaign (2000–2010) was aimed at solving urgent tasks in orthopedics, including the search for the mechanisms of disturbance of natural lubrication in joints and the development of novel medical procedures able to arrest cartilage wear. UN Secretary General Kofi Annan underlined in 2001 that diseases of the joints have become a global problem, a cause of suffering and disability for millions of people, and a burden on society; he appealed to scientists in various fields to promote the ideas of the decade by struggling against osteoarticular diseases.

The current paper is devoted to works made at the junction between biophysics, biotribology, and orthopedics. It provides convincing proof of the extent of the successes achieved in this field. Since the paper contains results in different fields of joints' biotribology (articular lubrication, **joint diseases, s**uperdrugs, **joint endoprosthetics**), we considered necessary to include in each section references to publications of different authors (including our previous publications).

2. Materials and methods

The objects under investigation were the following:

- synovia probes taken from patients joints during puncture and surgical procedures;
- substitutes of synovia (Synvisc, Hyalgan, Hya-ject, Orthovisc), and hyaluronic acid (HA); the reason for drugs selection was their proven clinical effect and availability;
- blood serum (BS) probes of patients and donors obtained at the day of experiment or stored at temperature −30 °C during 1–6 month, as well as BS modified by medicinal agents — anti-inflammatory (Diclofenac) and antimicrobial (Doxycycline) preparations;

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– samples of ultrahigh molecular weight polyethylene (UHMWPE) of "Hyrulen" grade with modified porous layer imitating cartilage.

On the purpose to estimate the structural order of synovia elements and their sensitivity to electromagnetic influence, the synovia probes were exposed until drying in electric field of 1.2 kA/m intensity and studied by optical and atomic force microscopy (AFM).

The method of electret-thermal analysis (ETA) was modified [5] and used for investigation the structure of synovia and BS. Thermally stimulated currents (TSC) were registered in the temperature range 20–180 °C.

The lubrication ability of synovia, BS and medicinal agents for joints local therapy was investigated by pendulum tribometer. The pendulum mass was 2.0 kg, the sliding velocity was 1.0 m/s, i.e. imitating the mean physiological load in human knee-joint. On the purpose to generate an electromagnetic field in the friction zone, solenoid was placed on the tribometer bearing [6]. The solenoid field intensity was 1.2 kA/m. The friction coefficient (f) was recorded according to the damped vibrations of the pendulum. The f meaning was determined by electronic data processing of signals proceeded from deviation angle sensor of the pendulum.

3. Results

The lubrication ability of compositions based on BS (investigated by pendulum tribometer) was found different when magnetic field was applied on the friction zone (Fig. 1). The value of friction coefficient for both compositions is more less when the magnetic field is applied to the friction zone.

The structures of BS and modified BS are shown on Fig. 2, *a*. Modification of BS by Doxycycline stipulates for release the liquid phase from albuminous structures and improvement of joints lubrication. The friction coefficient decreases in the time of magnetic field action (Fig. 2, *b*).

Samples of UHMWPE were subjected to frictional interaction at pressure 2 MPa and velocity 0.1 m/s. It was established that after friction in synovia, the samples display a different TSC spectra (Fig. 3), in particular — increasing the current peak corresponding to the polymer melting temperature.

4. Discussion

4.1. Articular lubrication

Modern notions of articular lubrication are based on the conception of the synovial medium as a tribological system. Cartilaginous frictional surfaces are in active interaction with synovia as structures exercising tribodestruction of synovial molecules, as sources of the biophysical field regulating the state of the electrically and magneto-sensitive lubricating film, and as absorbents of the synovial surfactant components.

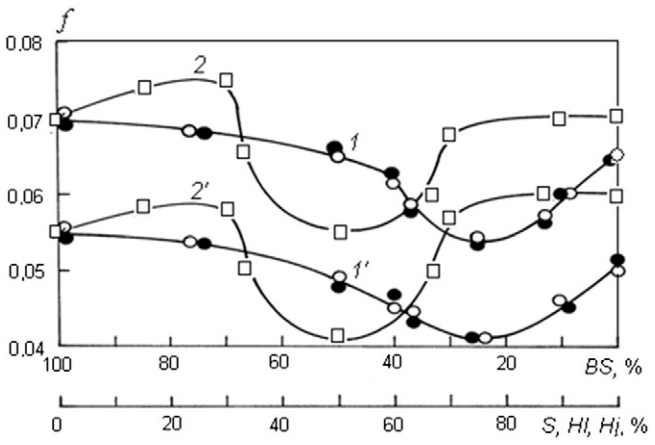

Fig. 1. Friction coefficient vs. lubricant composition and presence of magnetic field in the friction joint UHMWPE-steel. Compositions of lubricating fluids: *1*, *1′* — blood serum (*BS*) + Hyalgan (*Hl*, light dots) and blood serum + Hya-ject (*Hj*, dark dots); *2*, *2′* — BS + Synvisc (*S*); *1*, *2* — field is switched off; *1′*, *2′* — field is switched on, field intensity 1 kA/m, field action 50 min.

The boundary lubrication model proposed in [7] implies that synovial glycoproteids (complex proteins containing carbohydrate fragments) are absorbed by an electrostatic mechanism onto the negatively charged cartilaginous frictional surface. The nanolayer of glycoproteids adheres strongly to the cartilage and the subsequent components in the lubricating film are connected with glycoproteids by weak bonds. These bonds are formed between lyophobic components of synovia and experience the effect of repulsive forces. The sliding of cartilages leads to the breakage of such bonds because of their low resistance to shear.

Electrostatic interactions of the cartilage and the lubricant layer in a joint during friction presume the appearance of free charge carriers, or some other electrically non-equilibrium structures, in the synovial fluid. A direct experimental proof of the existence of these structures in synovia was obtained in the current decade by the method of electret-thermal analysis, used in the physics of dielectrics for studying electrets. The essence of the discovered quasi-electret state of synovia consists in the following. Heating at a constant rate drops of synovial fluid placed between a pair of electrodes, we can record the currents generated in the external circuit closing the electrodes, the density of which depends nonlinearly on temperature [5]. The temperature dependences of the thermally stimulated currents are similar to the TSC spectra of the electrets and are distinct for different types of synovia [2].

Another reason for the sensitivity of the articular lubricating film to biophysical fields is the liquid-crystalline state of synovia, inherent to all biological fluids and tissues of a living organism and critical for metabolic processes [8]. The lubricating synovial film in a joint is similar in structure to a cholesteric liquid crystal (LC) whose layers are parallel to the frictional surface [1]. The vectors of molecular orientation in the layers are turned at an angle to one another and form in combination a helical surface. Their mutual arrangement in the course of cartilage displacement brings about the phenomenon of low friction in a healthy joint [9]. The lubrication model proposed in [10] presumes that the frictional surface microrelief of cartilage imposes an orienting effect on the localization of shear stresses between the cholesteric layers.

The above-mentioned models comply with the hypothesis on the role of phospholipids (PL) in the wear resistance of joints [11]. Lipoids are a group of organic compounds that include fats and lipoids, including cholesterol. They are contained in all living cells and display high surface activity due to the polarity of their molecules. PL molecules are adsorbed on the negatively charged friction surface of cartilage by positively charged end groups. Movable Ca^{2+} cations link the molecules oriented along the normal to the friction surface with each other, thereby ensuring high cohesive strength and bearing capacity of the monolayer. Hydrocarbon tails of PL molecules are densely packed, thus adding hydrophobic properties to the cartilage surface. The authors of [12] are of the opinion that just the layer of adsorbed PL is responsible for boundary lubrication in the implanted joint endoprostheses.

One more theory of the boundary lubrication in joints [13] assumes that special structures that are secreted by fibroblasts (i.e., cartilaginous cells) form on the cartilage surface. Tribologists and orthopedists have long been challenged by the fact that boundary lubrication is present even in joints with degraded synovia and affected by osteoarthrosis. The term "lubricin" was proposed in [14] to denote the lubricating film existing on living cartilage. It is a nanosize structure that ensures *superlubricity*, i.e., the boundary lubrication of joints with an abnormally low friction coefficient. Using the methods of biochemical extraction, researchers have isolated the main component from lubricin, namely protein with molecular mass $MM = 345$ [15]. The level of lubricin is lowered in joints with traumatic synovitis. The concentration necessary for boundary lubrication to occur has become a measure for the engineering of cartilage tissues. In vitro tribological investigations using