

Artificial Joints: Chief Directions in Contemporary Orthopedics (Review)

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Abstract

Modern trends in joints investigation are presented, particularly the tribological aspects of natural and artificial joints. 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; 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 pharmaceutical substances; injection of drugs based on blood serum; development of a new generation of articular endoprotheses 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.

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, superdrugs, joint endoprosthesis), we considered necessary to include in each section references to publications of different authors (including our previous publications).

Retrospective Review

The term "synovia" was first introduced in orthopedics in the fifth century A.D. by reformer of ancient medicine Hippocrates; he defined the term as referring to the mucous contained in joints. Philosopher and physician Ibn Sina (Avicenna), who lived in Asia at the beginning of the 11th century A.D., described synovia as a medium wetting the joints so as not to let them go dry under friction. The efforts of practicing physicians in the second half of the 18th century resulted in elaboration of the notion of human joints as natural tribosystems, where mass exchange between joints and vessels takes place. By the beginning of the 19th century, synovia was found to be a synovial membrane producer. Only in the 1900s were the rheological properties of synovia related to the presence of hyaluronic acid (HA) [5].

In the 1960s and 1970s, biotribology emerged onto a new strategic level of investigations as a result of the invention of electronic microscopy; successes in histo- and cytochemistry, enzymology,

and immunology; the application of experimental procedures from biophysics, biochemistry, mathematics; and the computer analysis of results, among other factors. The English biotribological school, initiated by Duncan Dowson, have concentrated their efforts on studies of joint cartilage as a frictional material and a synovial carrier [6]. Works by the outstanding Russian arthrologist B.N. Pavlova, have defined the tendency towards a systematized approach to the study of joints. This trend is now embodied in the conception of the synovial medium in joints as a system of structurally and functionally interrelated parts: the synovial membrane, synovia, and joint cartilage [7].

The mechanisms of lubrication in joints have remained an open topic of discussion among biotribologists and orthopedists. As early as 1743, it was stated by J. Hunter in his report to the Royal Society that synovia is a lubricating material in joints [8]. Later, after 1920, the elasticity of cartilage was attributed to the isolation and absorption of synovia [9]. The ideas of the English physicist O. Reynolds were developed into a hypothesis that the cartilage surface geometry and synovial viscosity bring about a hydrodynamic effect during lubrication in joints [10]. This first attempt to apply the achievements of physics to orthopedic concepts proved to be an important point of departure for subsequent integrated investigations.

In 1934, English physicist E. Jones was the first to measure the friction coefficient in animal joints, putting the figure at $f = 0.005-0.020$ [11]. He concluded that lubrication in joints is hydrodynamic during motion and is boundary at the moments the motion starts or stops. It became clear that the Reynolds theory presuming the stiffness of friction pair components is of only limited applicability to the understanding of lubrication in joints. These restrictions were eliminated by Soviet tribologist A.N. Grubin, who included elastic strains on the components into his calculations and proved theoretically the possibility of realizing hydrodynamic lubrication in conditions admitting the existence of boundary lubrication only [12]. Grubin's theory was employed by Dowson to describe lubrication in cartilages, for which he proposed the term "elastohydrodynamic lubrication" [13], although this theory was later proved to be not universal [14].

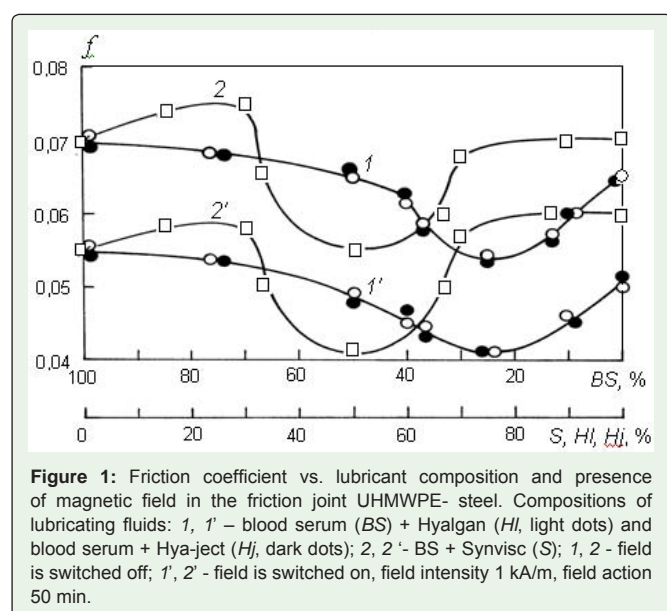
At the end of the 1950s, English orthopedist J. Charnley analyzed the results of experiments on a pendulum tribometer with animal ankle joints and differentiated them by isolating the cases when the ligaments and tendons remained undamaged and were artificially dissected. He concluded that boundary lubrication is dominant in joints [15]. The above-mentioned conclusions later developed into the opinion [16] that, depending on the friction regime and the state of the synovial medium, boundary lubrication, liquid lubrication, and the mode later identified by Kragelski as film starvation can be realized within joints. Regulation of the lubrication regimes in joints assumes the participation of cartilage in this process as an antifrictional material and a synovial carrier. Proceeding from this postulate, the following lubricating mechanisms in joints have been proposed.

Weeping lubrication is exercised by the synovia circulating between the lubricating layer squeezed between the rubbing cartilages and micropores of cartilaginous tissue [17]. This mechanism explains the low friction in the initial stage (static friction). The model of squeezed film lubrication implies that the cartilage props against a

synovial layer able to partially avert touching of the cartilage due to its bearing capacity [18]. Boosted lubrication is realized via enrichment of the lubricating layer with high-molecular proteinaceous compounds of synovia due to the filtration of low-molecular components into the cartilage micropores [19]. Thus, the lubricating layer acquires elevated bearing capacity and protects the cartilage from mechanical damage upon impact (chondroprotection). In spite of the high viscosity of synovia, its lubricity proves to be much higher than that of a high-viscous physiological solution [20]. In this connection, experiments were carried out in which the enzymatic destruction of HA macromolecules was initiated. As a result, viscosity was reduced, but the lubricity of the synovia was not impaired [21]. These achievements in the study of the lubrication mechanisms in joints have moved research onto a higher level.

Modern notions of articular lubrication are based on the conception of the synovial medium as a tribological system [22,23]. Cartilaginous frictional surfaces are found 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.

The boundary lubrication model proposed in [24] 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 drops of synovial fluid placed on a pair of electrodes at a constant rate, we can record the currents generated in the external circuit closing the electrodes, the density of which depends nonlinearly on temperature [25]. The temperature dependences of the thermally stimulated currents (TSC) 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 [26]. The lubricating synovial film in a joint is similar in structure to a cholesteric liquid crystal 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 [27]. The lubrication model proposed in [28] 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 [29]. 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 [30] are of the opinion that the layer of adsorbed PL is responsible for boundary lubrication in the implanted joint endoprostheses.

One more theory of the boundary lubrication in joints [31] 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 osteoarthritis. The term “lubricin” was proposed in [32] 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 $\text{MM} = 345$ [33]. 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 AFM have established that HA molecules adsorbed on the cartilage surface improve the lubricity of lubricin [34]. Proceeding from the above representations and taking into account the effect of exchange processes between the joint cavity and vascular beds of the organism, the authors of [35] have put forward a model presenting articulation as a smart friction joint.

Some Experimental Methods and Results

The objects under investigation were the following:

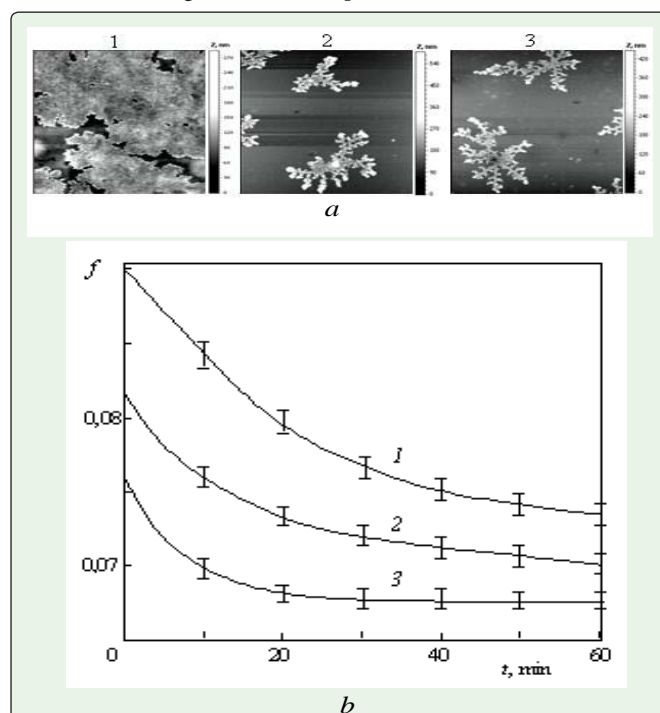
- synovia probes taken from patients joints during puncture and surgical procedures;

- substitutes of synovia (Synvisc, Hyalgan, Hya-ject, Orthovisc), 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;
- 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 [36] and used for investigation the structure of synovia and BS. Thermally stimulated currents (TSC) were registered in the temperature range $20-180^\circ\text{C}$.

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/sec, 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 [37]. 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.



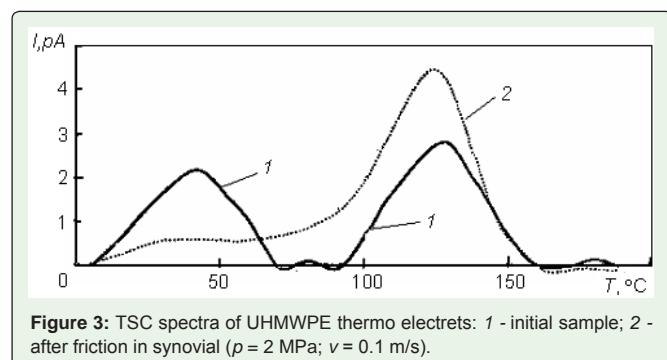


Figure 3: TSC spectra of UHMWPE thermo electrets: 1 - initial sample; 2 - after friction in synovial ($p = 2$ MPa; $v = 0.1$ m/s).

The lubrication ability of compositions based on BS (investigated by pendulum tribometer) was found different when magnetic field was applied on the friction zone (Figure 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 Figure 2a. 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 (Figure 2b).

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 (Figure 3), in particular – increasing the current peak corresponding to the polymer melting temperature.

Discussion of Main Directions in Joint Orthopedics

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.

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Proceeding from the above representations and taking into account the effect of exchange processes between the joint cavity and vascular beds of the organism, a model presenting articulation as a smart friction joint was put forward [35].

Modern-day friction joints are distinguished by a cybernetic property, meaning that the joints are able to adapt to operating conditions by varying the physicochemical structure of the contacting materials and the lubricant; the lubrication mode; the stress, charge and magnetic states of the components, etc., and are able to control the degree of this adaptation through a feedback mechanism. This concept, which arose at the end of the 1970s [38], is at present a criterion of engineering products perfection [39].

The synovial joint structure can be conceptualized [23] in the form of a tight tribosystem fit with subsystems of formation and circulation of the lubricating liquid, recovery of wear debris, and feedback, where the nerve center controls its functioning (Figure 4).

The synovial membrane incorporates capillaries of the blood vessel. Blood serum feeds the synovial membrane by permeating through the capillary walls (the meaning of the relation shown in the figure by a dashed line is explained below). The structure of the complex synovial compound is formed on the base of serum and HA produced by the membrane itself. As a result, synovia leaks into the articular cavity and fills micropores in the cartilage, forming a lubricating layer between the movably conjugated ends of the articular bones. The joint is lubricated through the mechanisms considered above. Cartilage wear debris and synovial tribodestruction fragments penetrate into the synovial membrane and are consumed by enzymes and macrophages. The products of this consumption are removed through the lymphatic and blood systems of the periarticular vessel. These interactions are controlled by a sympathetic nerve center possessing a feedback system, a blood vessel, and the synovial membrane. Nerve pulses change the permeability of the capillary walls and exert a vasodilatory effect that depends upon the biochemical parameters of blood and synovia. They may either activate or retard the generation of HA by the synovial membrane and regulate the biomechanical processes of the decomposition of wear debris and the dynamics of their removal. This results in optimized lubrication of the joint and improved rheological characteristics and lubricity of synovia. Thus, the joints are able to function reliably for an extended period, while their wear resistance depends on the overall state of health of the organism.

Local therapy of joint diseases

Joint diseases stem from failure of the structural elements of the smart friction joint. This violates the optimum lubrication regime of the cartilage. A striking example of this phenomenon is arthrosis, which affects 10–12% of the population [40]. Metabolic disturbance in the organism leads to contraction of lumen in the capillaries and impairs nutrition of the synovial membrane by the blood serum. As a result, synovia production reduces, its chemical composition and physicochemical structure alters, and it fails to properly perform its tribological and other functions in the joint. It is shown in [2] that joint diseases are accompanied by variations in synovia structure at the molecular level (molecular mass of proteins and HA reduce), at the level of complex compounds (breakage of hydrate membranes round polar synovial structures, recombination of the liquid-crystalline phase), and at the supramolecular level (recombination of supramolecular protein-polysaccharide formations). Infectious agents bring in the joint about immune complications, since the synovia accumulates pathological antibodies in addition to decomposition products. These antibodies bind in a specific way

with the proteins in the cartilage and synovial membrane so that the altered synovia displays pathological hostility towards the tissues of its own joint. This leads to a chronic autoimmune inflammation that may take the form of Bechterew's disease, rheumatoid arthritis, or some other condition. The structural recombination of synovia in a diseased joint is so strongly pronounced that it can be traced from TSC spectra [41].

Variations in the tribological characteristics of synovia are most explicitly seen from testing on a pendulum tribometer, in which the bearing unit is fit with a source of electromagnetic field that simulates the biophysical field of a natural joint [37]. The lubricity of the synovia in affected joints is lower than in normal ones, but it can be changed by the field [3]. The lubricity of the synovia affected by non-immune inflammatory diseases (synovitis, degenerative-dystrophic lesion) improves in electromagnetic field, which explains the effect of magneto-therapeutic procedures on joints. Lubricity of the synovia extracted from joints affected by immune pathology (Bechterew's disease, rheumatoid arthritis) deteriorates under the field effect [42].

Degradation of synovia promotes damage of the cartilage friction surface involving the stages of wearing with microgrooves, defibration of the cartilaginous tissue, and hydration of collagen fibers [43]. This process acquires avalanche-like behavior since the enzymes liberated from the affected cartilage catalyze and split the links in the synovial structure. The most extreme form of arthrosis is a "dry joint," in which in fact no lubricant is present due to atrophy of the synovial membrane along with cicatricial and spiking changes in the articular capsule.

The results of calculation by the finite-element method of the synovial lubricating film thickness h in natural and man-made joints were illustrated in [44]. The film thickness in a healthy joint is close to 2 mcm, while in an arthritic one it drops to 0.5–1.0 mcm, and it is even thinner, 0.2–0.5 mcm, in the endoprosthesis UHMWPE-metal. The value of h does not exceed 1.0 mcm in the endoprosthesis with metal-metal and ceramic-ceramic friction pairs. It is evident that the parameters of the lubricating film in the arthritic joint approach those of the implanted endoprosthesis. The efficiency of lubrication goes down with propagation of the disease and approaches the limit termed by Kragelskii as "threshold of external friction".

Injection of drugs into the articular cavity has gained recognition in the treatment of inflammatory and degenerative damage of the synovial medium in joints. This is in line with the modern trend in orthopedics of chondroprotection, i.e., protection of the articular friction pair from destruction and wear via medical prophylaxis aimed at stimulating the physiological regeneration of cartilage and normalization of the exchange between articulation and bloodstream in the organism. This means monitoring of the interactions between the components of the smart friction unit.

This situation has spurred the formation of a new direction within biotribology –tribomonitoring of medications [45]. One of the problems to be solved here consists in the fact that a drug injected into the articular cavity may exert an unpredictable, and sometimes adverse, effect on the mechanism of natural lubrication. The purpose of monitoring is to create a database of the tribological properties of the preparations for injections. It has been revealed that medications from a single pharmacological group may have extremely distinct tribological characteristics. The best lubricity is shown by preparations

Joint endoprosthetics

Endoprostheses are mechanical devices implanted into the organism to replace missing organs or their fragments. Arthroplasty is today the most extreme form of tribological correction of pathological joints. The above-described methods of chondroprotection are aimed at avoiding or postponing arthroplasty, which is an operation of alternative, mainly by elderly patients.

In the course of the development of endoprostheses, scientists have had to consider numerous medical, social, engineering, and other aspects, which are often inconsistent for correlation. It is thus not surprising that the current generation of articular endoprostheses resemble machine joints poorly adjusted for operation in the human body. It is critical to make endoprosthetic friction joints operate without failure for dozens of years. This problem is three-sided: 1) the technical lifetime restricted by the endoprosthesis failure due to limiting wear is to be not less than the remaining life of the operated patient; 2) wear debris of the endoprosthesis accumulating in the surrounding tissues and lymphatic gland may lead to post-operative complications; 3) aseptic instability (loosening) of endoprostheses is a result of contamination of the tissues by wear debris. The answers to questions of whether the compensating abilities of the organism are sufficient for the removal of foreign particles or whether their concentration grows over time, are strictly individual for every patient, type of endoprosthesis, and operation conditions.

The problem of wear resistance enhancement in endoprostheses came to the fore in the 1990s. In order to assist the body in removing wear debris, the endoprosthesis must be imparted with uncommon properties that would enable it to fulfill biophysical functions intrinsic to the synovial joint. The first steps in the development of the next generation of endoprostheses, which have already been implemented, can be grouped as follows.

The main difference between a natural joint and an endoprosthetic one is the presence of cartilage, with a system of micropores filled by synovia, which by liberation on the contact spots prevents the fatigue wearing of the joint that is so characteristic of endoprostheses. The structure of the cartilaginous tissue can be simulated by the material [57] based on UHMWPE employed in endoprosthetics, in which a system of communicating pores is made 1–30 mcm in diameter (Figure 5).

The procedure for creating such a layer on the friction surface of the polymer parts is described in [58]. This method improves the

antifriction properties of the parts without impairing their strength. *In vitro* studies have proved the high wear resistance of the material in the friction pairs against steel, the damping ability of the impact load [59], and the elimination of fatigue wearing [60]. A single-pole hip endoprosthesis, Neman, with a spherical head coated by a microporous layer [61] was undergoing successful clinical testing. The artificial cartilage injures to a minimum the natural cartilage, operating in tandem with it in the cotyloid cavity. The filling of the micropores of the polymeric material with a drug for preventing complications in the operative wound (antibiotics or substituting antiseptics) enables the transport of the drug into the zone of potential pathologic reaction. Based on the results of tribomonitoring, drugs have been identified that, aside of fulfilling their target function, are also effective as lubricating media providing lubrication of endoprostheses immediately after implantation. Prolonged liberation of the drug from the micropores of the polymeric material is made optimal so as to prevent aftereffects. The injection of the drug into the micropores of the artificial cartilage is preceded by treating of the friction surface in the HF plasma discharge or corona discharge [59].

The problem of reducing wear of the polymer-metal endoprostheses can be solved by designing them so that the polymer-metal and metal-metal contact spots alternate [22]. One such design [62] realizes the effect of selective frictional transfer, discovered by Kragelskii and Garkunov, in a tight endoprosthetic joint.

The operation on a joint involves the extraction of pathological tissues, which inevitably leads to distortion of the optimal distribution of the biofield in the joint. It appears expedient to compensate these distortions with the endoprosthesis itself. The simplest version of this compensation consists in giving endoprosthetic elements the property of generating an electric field, i.e., transferring the dielectric frictional materials into the electret state. The thermoelectret charge formed in UHMWPE elements is long-lasting (for years) during friction [63]. TSC spectra of the electret samples made of UHMWPE and subjected to frictional interaction in synovia display an increased intensity of the peak corresponding to the polymer melting point (Figure 3). This proves that the fragments of synovial destruction have been chemisorbed on the frictional surface owing to the electret field [64]. This layer ensures boundary lubrication in the endoprosthesis and protects the frictional surfaces from mechanical damage. The electrostatic mechanism of adsorptive layer formation results in accelerated healing of defects in the lubricating layer of the movable joint [65].

The physical model of artificial cartilage conceives of cartilage as a microporous layer on the polymer friction part of the endoprosthesis carrying the electret charge (surface density $\sigma < 10^{-6} \text{ C/m}^2$) that improves synovia adhesion to the friction surface and biological compatibility of the endoprosthesis. This layer serves at the same time as a reservoir for a drug and maintains its prolonged isolation onto the friction surface and operative wound. Biocompatibility of the described material has been estimated via examining tissue homeostasis, i.e., the structural and functional state of immunocompetent cells of peripheral blood [22]. The latter preserve their intrinsic regulating and anti-inflammatory functions in contact with the artificial cartilage. The identical reactions of the cells to natural pig cartilage and artificial cartilages confirm that the physicochemical structure of the developed implants approaches closely that of the natural cartilage.

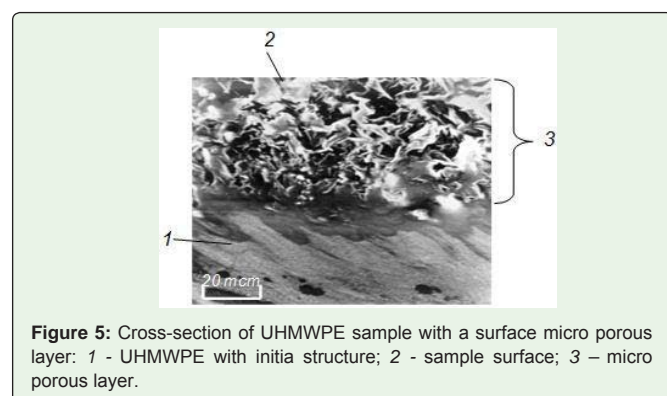


Figure 5: Cross-section of UHMWPE sample with a surface micro porous layer: 1 - UHMWPE with initial structure; 2 - sample surface; 3 - micro porous layer.

The above-cited results open new vistas in the application of physical fields to orthopedics. Their energy is transformed in patient's organism not only at the level of membranes and cells but also at the level of the lubricating layer in friction joints.

Conclusions

A relationship is shown between biotribology and the chief directions in contemporary orthopedics including: i) intraarticular chondroprotection exercised via local therapeutic methods based on tribological monitoring of pharmaceutical substances; ii) injection of drugs based on blood serum; iii) development of a new generation of articular endoprostheses able to simulate the biophysical properties of synovial joints.

The presented data are a vivid proof that Kragelskii's ideas, put forward as an attempt to raise the durability of movable junctions in machines and solve acute engineering problems, have proven to have vast applications in biotribology, which deals with living tissues and biological fluids. These ideas are now being applied to the solution of global problems in orthopedics, and to prevent suffering and disability of patients.

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