Biotribology of Cartilage Wear in Knee and Hip Joints
Review of Recent Developments

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Abstract: Nowadays, the problem of wear in the knee and hip joints is an important issue that concerns many people and still requires new solutions. In recent years, researchers dealing with knee and hip articular cartilage erosion continue to investigate the subject in terms of biotribology. In this study, recent developments and studies in this relevant area are been examined. By using the basic principles of tribology, useful new methods that can be used in the field of biotribology can be produced. Artificial joints designed using various materials such as metals, ceramics, polymers and composites are still being studied. New studies in this area will affect the development of implant technology. Different alloys or composites are currently being tested for new implant designs. Moving implants with a risk of wear are tested in laboratory conditions in simulator devices before they are used in the human body. Major topics such as nanotechnology, tissue engineering, orthopedics, tribology, biotribology, lubrication, organ transplantation and artificial organs, which are still important today, will be useful in the search for finding suitable solutions in the future in biotribological studies. This review article aims to provide an overview of in-vitro studies at the theoretical and laboratory conditions that must be performed prior to clinical investigation.

1. Introduction
Nowadays, cartilage wear problems are also increasing due to longer life, an increasingly comfortable life style, excessive weight gain, traffic and sports accidents. It is known that millions cases of damaged human cartilage are in need of repair. The need for this repair is found in the cartilaginous tissue, usually in joints with large loads, such as the hip and knee joints. Lubrication theories, such as hydrodynamic lubrication and boundary lubrication, which are well known and have been used for over fifty years in engineering science, are also considered ideal for use in biotribology. Biotribological knowledge also exploits the relevant lubrication theories to describe and explain friction and wear, even under the dynamic loading and sometimes compressed loading conditions encountered in the synovial joints. [1]

Biotribology is concerned with all aspects of tribology related to biological systems. It is one of the most exciting rapidly growing areas of tribological studies. As in many biological systems, for the solution of the problems in the operation of common systems, it is considered as one of the most important issues in terms of how our natural systems work, how diseases develop and how medical interventions are carried out. In this context, biotribology is an interdisciplinary science and technology that examines the surfaces of biological materials such as friction, wear, abrasion and lubrication. [2] [3]
For the medical solution of the problem arising from cartilage erosion which is called arthrosis, it is necessary to use the theoretical and practical solutions offered by the biotribology science. When looking for medical solutions, it has been recognized that the basic principles of tribology and biotribology are valid. They include basic topics such as friction, wear, wear debris, lubrication system, size change and losses. [6]

The knee joint is the most important joint in knee movements. The side and cross-links support the knee joint to ensure it remains in place. The femur and tibia bones in the knee joint are cross-linked to each other. One of the most important problems in the load bearing knee joint is the wear of the cartilage in this region. This wear directly affects the movement of the body. Associated joint diseases arise as arthritis and arthrosis. Arthritis is an inflammatory disease of the joints. Arthrosis refers to wear on joints. Arthrosis, which is usually seen in older people, is only rarely seen in younger people. This problem causes serious joint pain. Among the causes of arthrosis, in addition to factors such as excessive weight, lack of movement, body weight, and unbalanced weight loading, hereditary genetic predisposition is also a factor. [7]

2. How does knee cartilage wear (arthrosis) occur?

The knee joint has a cartilage layer that prevents friction in the bone heads. The cartilage, which is smooth and slippery, covers the moving parts of the bones. Normally, these ends have a soft and
elastic cartilage sheath. Continuous load-bearing cartilage gradually disintegrates and loses its flexibility. Finally, the cartilage becomes fragile. [8]

Cartilage injuries are most common in sudden impact injuries situations. Such injuries can occur while playing a sport or from the impact of a crash in a traffic accident. They are most commonly seen in the knee joint. After cartilage injuries to the knee, meniscus and cross ligament injuries may develop or symptoms may appear. [9] [10]

According to the information provided by the "Institute of Advanced Orthotics and Sports Institute of the United States", the number of "cartilaginous surgery" cases consisting of people of all ages in the United States alone is around 2 million a year.

2.1. Wear of “Cartilage to cartilage”

Mechanical-biochemical erosion involves the tribological interaction between the biological and mechanical system responsible for cartilage wear and disintegration. To advance forward in research, the cell response to mechanical stimuli and the related mechanical-biochemical erosion mechanisms must be further investigated for a complete picture of tissue degradation. [11] [12]

If the cartilage is completely eroded, the bone starts to rub against the bone. This situation causes the person pain and a reluctance to move. In some occupational diseases, in those who do not pay attention to proper shoe selection, cartilage wear at an early age may be seen in unilateral weight bearing, when using the joints badly. Apart from the knee joints, arthrosis can also be seen in the waist, hip and other joints. Although age progression is a risk, sometimes the disease can be seen even in young people. If the cartilage wears out once, regional healing is seen in young people, but it is not possible in today’s conditions to treat it in elderly people. [13]

When the materials of the body are classified, one of the various materials is cartilage. There are several types of tasks which are performed by various types of cartilage. Depending on its composition, cartilage is classified as cartilage (hyaline), fibrocartilage, or elastic cartilage. [12]

2.2. Wear of “Cartilage to artificial biomaterials”

One of the main reasons for disability worldwide is articular cartilage injury, that is arthritis resulting from degeneration. Although orthopedic surgeons and researchers continue their work on eliminating articular and cartilaginous defects, it is not possible to imitate the biological and biochemical properties of joint cartilage using existing research and development approaches. [14]

It is not possible to produce artificial cartilage with the same properties as the original. In this case, it is necessary to select suitable pairs of materials that are compatible with cartilage and which will move together in the same environment.

There is presently much experimental work in this area to develop the different kinds of artificial material that will come into contact with the cartilage or hold the cartilage and be placed in the body. For example, these materials alumina (Al₂O₃), cobalt-chromium (CoCr), titanium alloys (Ti₆Al₄V), stainless steel (SS), and cross-linked ultra-high-molecular-weight polyethylene (UHMWPE)’s impact resistance is high, the friction and abrasion resistance is very suitable for cartilage. [15] [16] [17] [18] There have been many studies involving the friction and abrasion tests of materials that will come into contact with or replace cartilage. The abrasion residues resulting from the friction and abrasion of these artificial materials with articular cartilages play an important role in the choice of material to be used. In various studies, nano-scale rubbing, roughness measurements and protein attachments of different artificial materials used against "bovine articular cartilages" have been examined histologically.
Because of the complex physiology, tissue regeneration and low recovery capacity of cartilaginous tissue, it is very difficult to heal the tissue. Unrepaired or improperly repaired lesions make the cartilage susceptible to osteoarthritis by creating malfunction tissues in terms of biochemical and mechanical strength. Applications such as FDA-approved cell-based treatments such as washing of the joint area, post-abrasive cleaning, lower cartilage piercing and micro-fracture are now being used to heal and restore focal cartilage defects in younger patients. [19] [20]

Despite the fact that cartilage in the tissue engineering that has developed over the last years for repairing damaged or damaged tissue is still cartilaginous tissue similar to natural articular cartilage, due to the complex hierarchical structure of natural cartilage, it is not produced. [21]

Artificial cartilaginous tissue, which tries attempted to mimic natural articular cartilage due to the complex hierarchical structure of true natural cartilage, has not yet been produced in sufficient detail, although it has worked in many of the tissue engineering methods developed in recent years to repair cartilage damage. [22] [23]

3. Treatment methods for cartilage

In adults, joint cartilage healing is insufficient. Unlike other tissues in the body, joint cartilage cannot be renewed after injury. However, due to injuries during sports, they may see regional damage in the joint cartilage of young individuals. In such cases, cartilage regenerative treatments can be performed because only a portion of the joint cartilage is damaged and the rest is intact. Treatment of knee cartilage erosion involves exercises without overloading to strengthen and support the muscles around the joint. Cartilaginous tissue cannot rebuild itself. There is no reversal for this common problem and medication is used before surgical treatment is considered. If there is no solution after all treatment methods have been tried to relieve joint damage after cartilage injuries, the joint is replaced by an artificial joint. For patient comfort, the joints are shaved and replaced with metallic implants by means of surgical intervention. [24]

3.1. Classical treatment methods for cartilage

Especially in the elderly, the ability of the joint cartilage to heal is inadequate. Unlike other tissues in the body, joint cartilage cannot renew itself after injury. For this reason, improvement in cartilage is not expected, and fluid which will make the joint less inflamed is injected, in order to reduce the friction by increasing the amount of ambient fluid. This method, which can be likened to the lubrication of hinges mechanically, is not effective in the long term because it is not possible to keep the fluid permanently in the liquid hinge region. [25]

In the case of drug supplements taken as oral tablets, a substance called "glucosamine" is used, this is already found in the body and is thought to be beneficial in the repair and shaping of joint cartilage. However, some people have also shown a reaction to this. It forces the muscles around the cartilage to work to reduce cartilage-cartilage friction and also to reduce excessive weight. [26] [27]

While there are many new techniques in the treatment of cartilage injuries, there is no clarification as to whether some lesions are in need of treatment or which treatment model is more appropriate for a given lesion.

New applications are increasing, but they are expensive. More objective data on cartilage injuries and newer efficient methods are needed to evaluate post-surgical outcomes. There are several published studies about the results of total joint replacement after post-surgical image evaluation and after surgery. In the future, more research will need to be done on cartilage surface reconstruction clinically.
In this regard, the development of common evaluation tools and standards of different engineering branches and orthopedic surgeons will achieve significant results. [28]

The International Cartilage Repair Association (ICRS), which was established in 1997, strives to establish a standardization system for the assessment of cartilage damage and repair. [29] Engineers from different disciplines and orthopedic surgeons continue to work on the search for new solutions in the treatment of cartilage damage. Engineering studies on non-destructive cartilage imaging are another engineering subject that has been studied. [30] The use of drugs that affect the gene system is being discussed in the treatment of rheumatic disorders in various articular cartilages. Innovations in cartilage imaging technology, interdisciplinary work such as stem cell technology, tissue engineering, bioengineering, and scientific discussions are ongoing. [31] [32]

3.2. **Current new treatment methods for cartilage damage**

After mechanical impact is applied to the joint region, progressive deterioration and damage to the cartilage occurs. Later, pain, swelling and loss of joint functions occur. After the treatment of the cartilage system, the advantages and disadvantages of the procedure can also be discussed. Many efforts have been made to develop tissue-engineered grafts or patches to repair focal cartilage and cartilage defects. [33] [34]

3.2.1 **Micro-fracture method.** In this method, small holes are created in damaged cartilage areas. Then, the stem cells in the bone marrow are removed and transported to the damaged small hole areas, creating a cartilage patch. Cylindrical solid cartilage taken from the surfaces of "non-load bearing" areas can be transferred as patches to damaged areas of need. The advantage of this method is that it is completely arthroscopic, no complicated equipment is required, and it is effective and cheap. The disadvantage is that the newly formed cartilage is structurally different and weaker than the normal joint cartilage. The effect is reduced in large areas of 3 cm². [35][36]

3.2.2 **Cartilage transplant method.** Scientists are continuing their new work on in-vitro models to develop new treatment technologies that can be applied now and in the future. After the patient's own solid cartilage cells are produced in the laboratory environment, they are then transplanted in the damaged region. Autogenous cartilage transplantation, whereby cartilage can be taken from one part of the body and transported to another, is a generally accepted method in reconstructive surgery. In-vitro engineering studies for cartilage tissue are promising. The host’s response to the implant materials determines whether the size of the implant materials to be transported will be small/large. [1] [37] [38]

3.2.3. **Cartilage and meniscus allografts method.** The meniscus was known as a useless surplus in the past, but today it is known to have very important functions. The functions of the meniscuses are as follows load transportation, load transfer, and joint lubrication and helping with the screw home mechanism. In the absence of anterior cruciate ligaments, it aids secondary anterior-posterior stabilization. Nowadays, no implant can replace total meniscus loss. It is indicated only in segmental defects.[39]

This method is a good alternative to knee prosthesis in young patients with large bone and cartilage damage. [40]

3.2.4 **Mesenchymal stem cell repair (MSC) method.** Stem cells, according to their period of development, are divided into the following groups: embryonic, stimulated pluripotent and adult cells. Among them are embryonic stem cells, cartilage, bone, and muscle, but are not yet differentiated. Joint cartilage injuries (arthritis) cause permanent damage to the joint. In this case, there are many people in this world who live as disabled people.
The work done by "mesenchymal stem cell repair" is one of the most important current areas of research for disability. Muscles, bones, cartilages, etc., have the potential to transform into different tissues in the body. MCS is found in the gel matrix of human bone marrow. If it is placed in the damaged cartilage region, new cartilage tissue develops. [20] [23]

4. Biotribological research support for cartilage treatments.

4.1. Simulation programs

By using biomimetic science in real joint systems, problems are solved with the support of engineering subjects such as biomechanics, biotribology, contact mechanics, and lubrication systems. When it is defined by the classical macroscopic approach in tribology, properties such as roughness and friction coefficient of surfaces, properties of lubrication and properties of lubricant and relative speeds of moving surfaces are within the scope of this heading.

Simulation applications can be made for different sample applications by changing all the contribution properties in this regard. There are also different studies based on the assumption that joint movement is an important part of mechanical conduction in the synovial joints. Software and programs that simulate different applications where sliding, rotating, or different versions of these exist together have also been developed. [41] [42]

4.2. Mechanical fatigue tests

Mechanical fatigue testing machines have also been used in studies to observe the in-vitro results of applications such as wear, friction, and lubrication.

There is still a lack of information about the dynamic process of cartilage damage, which is the result of the negative consequences of social effects. Experimental system studies are carried out to perform a series of cycles designed to produce mechanical fatigue in in-vitro environments that fulfill in-vivo conditions. Different results are obtained by changing the specific cycle loading numbers to obtain the functional stress, strain, wear, and texture response results. The surface analyses obtained are examined histologically and microbiologically. Fatigue tests performed under pressure or without pressure are also used. In mechanical fatigue tests, the size of the load, the applied frequency, the amplitude of the alternative load, the thickness of the sample, etc., affect how the result will be formed. [43]

4.3. Wear and friction tests

In different studies, a variety of materials were applied to see the results of friction and abrasion of biomaterials on cartilage. It is the UHMWPE that causes the least wear and tear on these materials and the most damaging is CoCr alloy.

Scientists are currently working to develop new treatment methods for degenerative joint diseases by performing different studies to understand the tribological properties of joint cartilage. The results obtained by the sliding and rotation mechanisms in the experiment on the friction and wear behavior of bovine cartilage applied in dry and wet environment using liquid film formation and boundary lubrication technique were evaluated. The experiments were repeated with a very high number of cycles. [19] [44] [45]
4.4. Lubrication tests

Cartilage of different shapes and composition performs many functions in the body. There are three types of cartilage: joint cartilage, fat and elastic cartilage. Cartilage functions as a bonding material or as lubrication material on the loading surface. Thanks to cartilage support, organs such as the ears, nose and food pipe remain intact. Lubrication of the joints is performed by means of cartilage which is a natural lubrication mechanism using bio-fluid synovial and bio-fat. [12] [46]

![Figure 3. Striebeck curve diagram [47]](image)

1.1. Knee and hip joints are living tribological systems with a very low coefficient of friction and no similarities. It is not possible to produce a material or mechanism with these properties. The reason for the low friction between the cartilaginous surfaces is believed to be due to the sliding molecular layers between the cartilaginous surfaces.

![Figure 4. Diagrammatic representation of dry contact and lubrication regimes [48]](image)

Thanks to the excellent tribological mechanism of cartilage, there is a unique lubrication system consisting of both the presence of a pressurized liquid medium and a boundary lubrication mechanism supported by large fat molecules attached to the surface. [49] [50]
4.5. Biocorrosion tests

Rapid degradation of the biomaterial is caused due to the microbial film layer on the surface of the biomaterials. The mechanism of formation of biocorrosion is still not fully resolved. Very rapid biocorrosion occurs in the environment of hydrogen and oxygen in the metals. Polymers also develop as corrosion/degradable. When in-vitro and in-vivo experiments are performed to produce different implants suitable for the body, the results give a certain amount of results. However, no any artificial materials give results equivalent to the natural body materials.

In recent years, polymer biomaterials have to have properties that vary from place to place. The biodegradable property is desirable in fracture fixation plates, but not in implants that involve the hip and articular cartilage. Meanwhile, the hope that the interstitial spaces of artificial polymers, which have started to be used as scaffolding structures in tissue engineering, can be filled with the structure to be developed by the patient’s one's own stem cells, opens new horizons. Artificial biomaterials are being researched natural or artificial polymer types for different applications. [51]

Biodegradable polymeric biomaterials are used as fracture fixation plates. They are also used as 3D scaffolds in tissue engineering thanks to their porous construction. This property of biodegradable polymers also makes it the preferred material for the development of controlled drug release devices. The development of these properties is hoped to lead to the introduction of polymers to be used in cartilage structure. [52] [53] [54] [55]

4.6. Abrasively Bio-Corrosion Tests

It is inevitable that abrasive particles will form after friction. Normally, the particles are eliminated and bleeding can be stopped. If the resulting particle load exceeds the elimination capacity, failure occurs. [56]

If residues are trapped in cartilaginous interfaces, increased wear due to mechanical friction occurs and wear increases the friction of the intermediate zone and causes more wear and tear. The debris particle will accelerate the onset of wear on the environment. Preventing corrosion and mechanical abrasion will also slow the formation of debris. [57] [58] [59]

5. Conclusion

The latest developments in classification and different approaches to treatment are constantly ongoing. In small blood vessels in small damaged chambers that are intentionally created in cartilage, there is a possibility that the stem cells may turn into cells that resemble cartilage if the surrounding conditions are favorable. Recently, mold implants called “matrix” have been developed so that the said root cell can be held more tightly in damaged mini chamber regions. Any work that can be done in order to reduce friction between cartilages will be beneficial. However, if the damaged cartilage layer is to be removed from the medium, the artificial biomaterials that will retain it should be selected to form the appropriate pair. Properly selected pairs exhibit no wear behavior at first, but wear can occur over time.

No artificially produced cartilage will ever be as good as natural original cartilage. However, more research on cartilage will continue to be carried out in order to allow people to lead a more productive and comfortable life with a longer life expectancy.
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