Tribology in Human Joints

K. Ikeuchi
Institute for Frontier Medical Sciences, Kyoto University
Kyoto 606-8507, Japan

1. Introduction

During normal walking, human lower leg joints support more than 3 times body weight because muscle forces are added to the net body weight, and contact pressure between articular cartilage exceeds 1 MPa. Though articular cartilage is not a strong material, it can survive as long as a human life under high load and low velocity. Therefore, many researchers with different backgrounds have been proposed many lubrication models to explain the reason for low friction and low wear in natural joints. This paper reviews the studies of lubrication in human joints from the standpoint of a tribologist.

2. Materials and composition of natural joints

Sliding surface in joint is covered with articular cartilage. It is a soft tissue composed of cells (chondrocytes), polysaccharides, collagen fibers and 80 wt% water (1). The cells are surrounded with matrix of amorphous polysaccharide substances and collagen fibers. The moment external force is applied, the articular cartilage behaves like an elastic solid. Then, the cartilage continues to creep with pressure induced water flow through the cartilage. For instantaneous or dynamic loading, elastic modulus of the cartilage is estimated to be about 10 MPa (2). The rate of flow in the cartilage decreases gradually with time. Elastic modulus is estimated to be about 1 MPa for the final equilibrium condition when creep deformation diminishes. The mechanical property of the articular cartilage is expressed by poro-elastic model or biphasic model (3). The articular cartilage attaches firmly to sub-chondral bone plate.

The synovial fluid includes hyaluronic acid, proteins, cells, phospholipids and inorganic ions. Viscosity of the synovial fluid is higher than pure water due to hyaluronic acid supplied from synovial membrane. Viscosity of synovial fluid decreases from 1 Pa s to 0.01 Pa s with an increase of shear rate (2).

3. Soft-EHL (4)-(7)

The articular cartilage and sub-chondral cancellous bone is deformed by pressure applied to the cartilage surface. Therefore, the major lubrication mode of natural joints is soft elasto-hydrodynamic lubrication (soft-EHL). In other words, most of joint load is supported by fluid pressure. According to a numerical analysis of EHL film in human ankle joint (8), fluid film thicker than 1 μm is formed between cartilage surfaces during walking. The fluid film is formed by hydrodynamic wedge effect and maintained by squeeze film effect. However, it is unlikely that complete fluid film is always kept in a human joint because human motion is not always periodic. For example, when a human joint is moved suddenly after a long rest under load, the cartilage surfaces inevitably slide contacting to each other. Then, supplemental lubrication mechanisms act to reduce contact pressure and wear (3), (5), (7).

4. Weeping lubrication (9)

As the articular cartilage is a porous and elastic material, water flows through the cartilage, flows out of the cartilage to the gap or flows into the cartilage. However, rate of flow into the cartilage and out of it is negligibly small if the cartilage is pressed by fluid (6) because its permeability is very low. However, if the cartilage is pressed with solid or porous material, pressure gradient arises in the layer beneath the cartilage surface in direction normal to the surface. As the layer is very thin at the moment of contact, pressure gradient becomes very steep even if contact pressure is low. Therefore a small amount water weeps from the cartilage to the gap and lubricate the cartilage surface for a while (10). The articular cartilage detects lubrication condition and responds to direct contact pressure.

According to an experiment (11) with an end-face friction apparatus for cartilage-flat disk combination, creep deformation continues for 1 hour until creep deformation velocity approaches zero. This result suggests that weeping of water continues for 1 hour. On the other hand, friction continues to increase for more than 2 hours until coefficient of friction becomes constant. From the difference in these intervals, it may be concluded that the effect of water exuded from the cartilage continues for more than 1 hour. This period is much longer than the interval estimated for squeeze film effect. Then, it is likely that another lubrication mechanism takes place to keep low friction coefficient for long time.

5. Surface gel hydration lubrication

A thin bright layer is observed on the cartilage surface with an optical microscope. Sasada (12) presented a new lubrication model with the surface layer of hydrophilic macromolecules and water. The main source of the macromolecules is the cartilage while molecules from synovial fluid bond to them. Water molecules are attracted by the macromolecules and separate the compliant branches of macromolecules from the ones on the mating surface. The restricted water has intermediate property of sol and gel. Friction and wear are kept low by the water rich surface layer. Though the surface gel hydration lubrication resembles to squeeze film action, the effective time of the former is much longer than that of the latter because of attractive force between the water and the macromolecules.

Similar low friction is experienced at skating, skiing, walking on a rock covered with wet slippery moss or polymer surface grafted with hydrophilic materials. According to experiment with polyurethane graft polymerized with dimethylacrylamide (13), friction depends on water content of the surface layer. Low friction coefficient is kept long even at extremely low sliding velocity.

6. Boundary lubrication

The boundary lubrication is the final mechanism that acts even when other lubrication effects fails. Proteins from the synovial fluid reduce friction and wear (14), (15). γ-globulin is the most effective boundary lubricant among the proteins included in synovial fluid. The synovial fluid also include phospholipids. A small amount of dipalmitoyl phosphatidylcholine attaches at the hydrophobic region of the cartilage surface reduces friction after the surface lubricating layer is removed by treatment with detergent (16). While hyaluronic acid contribute to fluid film lubrication by increasing viscosity, it does not affect boundary lubrication.

7. Discussion

As stated before, the major lubrication mode in a human joint is soft-EHL. If complete fluid film is kept throughout the cartilage surface, the lubrication condition depends only on joint profile, elastic modulus of the cartilage and viscosity of synovial fluid. Therefore, we would be able to realize an artificial joint of a material with low elastic modulus regardless of its anti-wear property. However, wear resistance of sliding surface is inevitable even for a compliant surface artificial joint because direct contact is unavoidable in artificial joints as well as natural joint.

Generally speaking, simple lubrication mechanism is desired for an industrial bearing to confirm reliable operation. In contrast, in a human joint, complex lubrication mechanisms collaborate to make the articular cartilage survive as long as a human life. The difference in design concept is due to the difference in history. Natural joints has obtained reliability through the evolution for hundreds of million of years. However, I believe that we can get many ideas from the human joints.

8. Summary

The major lubrication mode of human joint is soft-EHL while supplementary lubrication mechanisms affect at mixed lubrication region. This paper focuses weeping lubrication and surface gel hydration lubrication because they are not recognized in industrial bearings.

References

(1) M.A.R. Freeman, Adult articular cartilage, Second edition, Pitman Medical, U.K., 1979, 1-8.

(2) P.S. Walker, Human joints and their artificial replacement, Charles C Thomas Publisher, U.S.A., 1977, 122.

(3) V.C. Mow, Biphasic creep and stress relaxation of articular cartilage in compression: Theory and experiments, J. Biomechanical Engineering, Trans. ASME, 102, 1980, 73-84.

(4) D. Dowson, Modes of lubrication in human joints, Proc. Instn. Mech. Engrs., 181(Part 3J), 1966-7, 45-54.

(5) T. Murakami, The lubrication in natural synovial joints and joint prostheses, JSME International J., Ser. 3, 33(4), 1990, 465-474.

(6) K. Ikeuchi, The role of synovial fluid in joint lubrication, Lubrication and Lubricants (Eds. D. Dowson), Elsevier, Amsterdam, 1995, 65-69.

(7) T. Murakami, H. Higaki, Y. Sawae, N. Ohtsuki, S. Moriyama and N. Nakanishi, Adaptive multimode lubrication in natural synovial joints and artificial joints, Proc. Instn. Mech. Engrs, Part H, 212, 1998, 23-35.

(8) J.B. Medley, D. Dowson and V. Wright, Transient elastohydrodynamic lubrication models for the human ankle joint, Engineering in Medicine, 13 (3), 1984, 137-151.

(9) C.W. McCutchen, The frictional properties of animal joints, Wear, 5, 1962, 1-17.

(10) K. Ikeuchi and M. Oka, A model analysis of squeeze film effect in a hip joint, Thin Films in Tribology (Eds. D. dowson), Elsevier, Amsterdam, 1993, 513-520.

(11) K. Ikeuchi, M. Oka and S. Kubo, The relation between friction and creep deformation in articular cartilage, Dissipative Processes in Tribology (Eds. D. Dowson), Elsevier, Amsterdam, 1994, 247-252.

(12) T. Sasada, Nature of joint friction and "surface gel hydration lubrication", Submitted to J. Japanese Society for Clinical Biomechanics and Related Research, 21, 2000.
(13) K. Ikeuchi, T. Takii and H. Norikane, Water lubrication of polyurethane grafted with dimethylacrylamide for medical use, Wear, 161, 1993, 179-185.
(14) H. Higaki and T. Murakami, Role of constituents in synovial fluid and surface layer of articular cartilage in joint lubrication (Pt.1) Experimental study in application of enzyme digestion, Japanese Journal of Tribology, 39 (7), 1994, 859-869.
(15) H. Higaki and T. Murakami, Role of constituents in synovial fluid and surface layer of articular cartilage in joint lubrication (Pt.2) The boundary lubricating ability, Japanese Journal of Tribology, 40 (7), 1995, 691-700.
(16) H. Higaki, T. Murakami, Y. Nakanishi, H. Miura, T. Nawatari and Y. Iwamoto, The lubricationg ability of biomembrane models with dipalmetoyl phosphatidylcholine and γ-globulin, Proc. Mech. Engrs., Pt. H, 212, 1998, 337.