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Importance of adaptive multimode lubrication mechanism in natural synovial joints

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ABSTRACT

The superior tribological performance in natural synovial joints with low friction and minimal wear appears to be actualized by not single lubrication mode but the synergistic combination of various modes from the fluid film lubrication to boundary lubrication corresponding to the severity of rubbing conditions. We have conducted the biphasic finite element analysis and some experimental studies for articular cartilage to elucidate this ingenious lubrication mechanism from the viewpoint of the adaptive multimode lubrication mechanism. In this paper, the effectiveness of different lubrication modes such as biphasic, boundary, gel-film and hydration lubrication particularly at low speed conditions is discussed.

1. Introduction

The healthy natural synovial joints have excellent load-bearing characteristics with extremely low friction, high load-carrying capacity, good shock absorption capability, smooth movement with stability and minimum wear (long durability) even in heavily loaded hip, knee and ankle joints. In various daily activities, this superior lubricating performance appears to be actualized by not single lubrication mode but the synergistic combination of various modes from the fluid film lubrication to boundary lubrication corresponding to the severity of rubbing conditions, as pointed out by Dowson [1]. At the symposium on “Lubrication and Wear in Living and Artificial Joints” (1967), he indicated that “the major lubrication mechanism would seem to be some form of elastohydrodynamic action determined by sliding or squeeze film action between porous surfaces with boundary lubrication providing the surface protection in cases of severe loading and little movement. The human joint seems to operate in the ‘mixed’ lubrication – sometimes elastohydrodynamic and sometimes boundary lubrication” [1]. For example, in case of 100 m running by U. Bolt at world record at 9.58 s as 40.92 steps with average running speed at 10.4 m/s (37.6 km/h) (2009), the average sliding speed of femoral chondyle in knee joint is estimated as to be probably higher than 300 mm/s (for 0.23 s/step), at which hydrodynamic pressurization is expected to support the joint loading. In contrast, at slow movement after long stationary standing, some local direct contact may occur in thin film condition, where boundary lubrication or alternate protective lubrication mode is expected to become effective. More than 35–50 years ago, various lubrication mechanisms such as weeping [2], boosted lubrication [3], biphasic lubrication [4], boundary lubrication [5] and others had been proposed for natural synovial joints.

As mentioned above, the lubrication modes may change for flexion-extension motion during normal walking motion composed of the loading stance phase with peak loads of about three to four times body weight and the swing phase with medium flexion at light load. Unsworth et al. [6] suggested on the basis of pendulum tests of human hip joints that the lubrication modes change from the elastohydrodynamic lubrication mode with squeeze fluid film action at heel strike and entraining action during load-bearing stance phase followed by short time boundary lubrication after squeeze action at toe off to the fluid film lubrication during swing phase. Thereafter, Roberts et al. [7] measured the frictional torque of cadaveric hip joints in hip function simulator for walking motion and observed that friction at high load was maintained as low due to squeeze film effect even with very low viscosity condition while the transition from mixed lubrication to full

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fluid film lubrication was observed at low load at viscosity range of 0.025–0.1 Pa s for synovial fluid. On the possibility of fluid film lubrication during walking, Dowson and Jin [8] applied the micro-elastohydrodynamic lubrication (micro-EHL) concept to ankle synovial joint as simplified model covered with soft elastic layer of sinusoidal surface roughness during walking, where they found that the surface roughness itself causes local pressure perturbations to occur which flatten the initial surface asperities. Thus, it was shown that higher ratio of the minimum fluid film thickness to the reduced surface roughness in loaded conjunction zone supports the possibility of full fluid film lubrication. In their analysis, however, the flow in articular cartilage is excluded.

In a numerical analysis of deformation and lubrication in a hip joint under step load by Ikeuchi et al. [9,10], the flows in both the articular cartilage and the gap between cartilages were considered. In their analysis, the local contact points appear in a circumferential zone while high pressure fluid was trapped at the center of loading zone just after step loading, and an outward flow to the gap from the cartilage at contact point was caused by a significant pressure gradient near the surface accompanied with creep deformation. The squeeze film behavior with creep deformation and outward flow from cartilage contribute to the improvement in the conformity and the lubrication. These behaviors were confirmed by experiment [10,11]. Furthermore, it was confirmed that no creep deformation is detected when the cartilage is pressed by fluid alone which suggests that the cartilage can be simplified as a non-porous elastic material under full fluid film lubrication condition.

As described above, in natural synovial joints where both the articular cartilage as biphasic compliant bearing material and the synovial fluid containing effective lubricative constituents play the important roles in sustaining low friction and minimal wear, various lubrication modes are likely to function depending on the severity of operating conditions in various daily activities. This superior lubrication mechanism was called “adaptive multimode lubrication” based on summarized review of related studies by Murakami [12]. We have made collaborative efforts in elucidation of this ingenious lubrication mechanism in natural synovial joints from the viewpoint of the adaptive multimode lubrication mechanism [13–16] as explained in this paper.

At the 43rd Leeds-Lyon Symposium on Tribology organized on the theme of “Tribology (The Jost Report – 50 years on)”, many papers showed with active discussions that tribology can play important roles to appropriately control and optimize friction and wear behaviors, lubrication, bearings with interdisciplinary sciences and technologies including mechanical engineering, physics, chemistry, materials science and lubricant technology for more than a half century in various fields. After 6 years (in 1972) from the introduction of tribology in 1966 [17], new related field of Bio-Tribology was introduced as “the aspects of tribology concerned with biological systems” by Dowson and Wright [18]. The lubrication mechanism of natural synovial joints with extremely low friction and minimal wear for longer life has been one of the most valuable and attractive subject in biotribology.

In lubrication mechanism of natural synovial joints, the articular cartilage as bearing surfaces appears to play important roles together in close coordination with synovial fluid which has superior lubricating ability [19]. Articular cartilage is not simple soft elastic layer but has biphasic property with fiber-reinforced hierarchic structure (Fig. 1) [20] and lubricious surface such as lamina splendens [21–23]. As shown in transmission electron-microscopy (TEM) image of transection of articular cartilage (Fig. 2(b)) [24], top surface is constructed by acellular and non-collagenous amorphous layer and covered with continuous adsorbed films composed of mainly phospholipid bilayer and fibrous molecules.

In this paper, the important features of adaptive multimode lubrication particularly for thin film condition at slow movement are described where hydrodynamic lubrication has little lubricating effect.

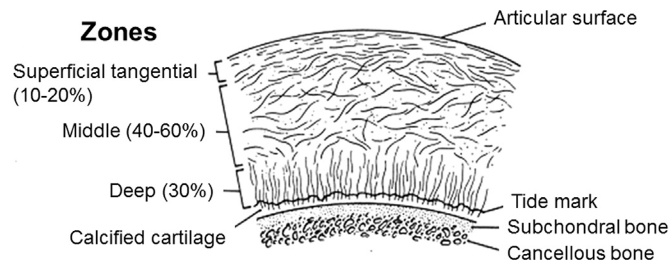

Fig. 1. Hierarchic and fiber-reinforced structure of articular cartilage. Reproduced with permission from Ref. [20].

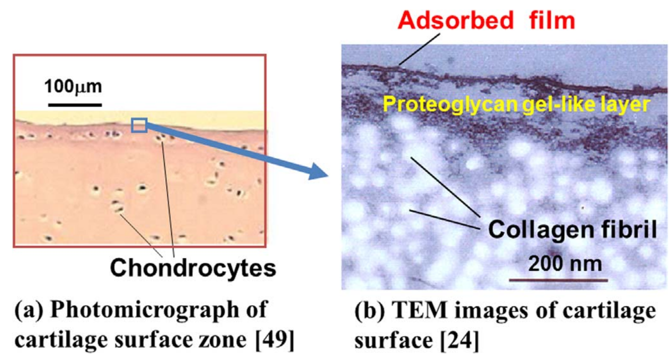

Fig. 2. Cross-section of articular cartilage as micrograph and TEM image.

That is, our researches on the biphasic, boundary and gel film lubrication are shown with considering the effect of hydration lubrication.

2. Biphasic lubrication

The articular cartilage has high water content from 70% to 80% in tissue composed of type II collagen, proteoglycan and chondrocytes, and thus exhibits a time-dependent biphasic behavior due to the simultaneous coexistence of solid and liquid phases [25]. Furthermore, it is noted that lubrication mode depends on the extent of exudation and rehydration in various activities. The load support by interstitial fluid pressure in biphasic cartilage controls the friction and deformation.

In the previous paper by Mansour and Mow on biphasic lubrication [4], it was shown that the normal healthy articular cartilage is capable of generating its own film of fluid lubricant at medium sliding speed of 25.4 mm/s to 76.2 mm/s. It is noticed that the movement of interstitial fluid at the surface is circulatory, i.e., it is exuded in front and near the leading half of loading conjunction zone and imbibed behind and near the trailing half. In contrast, it was suggested that pathological cartilage with porous surface of high permeability and low stiffness cannot maintain fluid film formation. In their paper, the time-dependent frictional behavior for cartilage with local direct contact at slow speed was not discussed.

After about two decades, Forster and Fisher [26,27] examined the influence of loading time, unloading and lubricant on the time-dependent friction of biphasic articular cartilage in sliding tests at low speed of 4 mm/s in mixed lubrication regime and confirmed that the load carriage by the fluid phase becomes an important factor influencing friction, and the friction force was proportional to the load carried by the solid phase. The theoretical formulation of a boundary friction model for biphasic articular cartilage was proposed and validated by Ateshian et al. [28–31]. Furthermore, it was indicated that the Peclet (Pe) number as the ratio of convective velocity of sliding and the diffusive velocity of interstitial fluid flow for rubbing condition controls the effectiveness of interstitial fluid load support [31]. As shown by the following formula, the time-depending changes in friction