Influence of Synovial Fluid Pressure on Biphasic Lubrication Property in Articular Cartilage

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Abstract

The influence of synovial fluid pressure in wedge-film gap on the biphasic lubrication property of articular cartilage during sliding motion has not been discussed in previous studies. We hypothesized that synovial fluid pressure generated in a wedge-film shaped gap just ahead of cartilage contact region suppresses the effusion of interstitial fluid in articular cartilage and that this enhances biphasic lubrication ability of articular cartilage. In the present study, we determined fluid pressure distribution in the wedge-shaped gap. We, then, also performed a friction analysis to compare the coefficient of dynamic friction of standard poroelastic model with that of synovial fluid pressure (SFP) model. In SFP model, the effusion of interstitial fluid from articular cartilage was regulated in accordance with the pressure difference between measured synovial fluid pressure and analyzed interstitial fluid pressure at the surface. Experimental results revealed that the maximum fluid pressure increased with the increase of sliding speed. The coefficient of dynamic friction was lower in SFP model than in standard model with the largest difference of 25% observed at 30 mm/s. Effusion of interstitial fluid from articular cartilage near the periphery of contact region was more suppressed at higher sliding speeds, which resulted in a better lubrication property due to higher interstitial fluid pressurization. These results suggested that synovial fluid plays important roles not only in hydrodynamic lubrication but also in biphasic lubrication by suppressing the effusion of interstitial fluid in articular cartilage.

Keywords
articular cartilage, biphasic lubrication, synovial fluid, interstitial fluid, hydrodynamic pressure

1 Introduction

Articular cartilage has a significant lubrication property as a bearing material which has been explained by traditional lubrication theories including boundary lubrication [1,2], hydrodynamic lubrication [3-5], mixed lubrication and so on. Recently, many investigators have focused on the biphasic lubrication [6] for the consideration of the lubrication mechanism of articular cartilage. This theory employs the framework of the biphasic theory developed by Mow et al. [7], which models cartilage as a poroelastic material consisting of solid and fluid phases and both phases play roles in resisting to externally applied compressive loads. In the biphasic lubrication, the frictional resistance is kept low as the shear resistance of fluid phase that bears the most of the applied load is negligible. Caligaris and Ateshian [8] found that the interstitial fluid pressurization occurred in response to articular motion contributed to reduce the frictional resistance of articular cartilage under physiological conditions.

Previous studies on the biphasic lubrication [9-13] have focused only on the behavior of interstitial fluid in articular cartilage, and the synovial fluid behavior outside articular cartilage, and inflow and outflow of water between cartilage matrix and synovial fluid have not been considered. In contrast, previous studies on the hydrodynamic lubrication have focused only on the behavior of synovial fluid outside of cartilage, without paying attention to the behavior of interstitial fluid. As is known for hydrodynamic lubrication, synovial fluid pressure is generated by the squeeze-film effect and the wedge-film effect. Hou et al. [14] and Jin et al. [15] have considered the effect of porosity of the articular cartilage on squeeze-film effect involving film thickness and inflow of water in the human joint. However, the effect of synovial fluid pressure generated by the wedge-film effect on the biphasic lubrication property have not been considered. Therefore, we hypothesized that synovial fluid pressure generated in a wedge-shaped gap between confronting cartilage surfaces suppresses the effusion of interstitial fluid and that this enhances biphasic lubrication property in articular cartilage.

Our previous study [16] indicated that synovial fluid...
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Pressure in the wedge-shaped gap enhances the biphasic lubrication property of articular cartilage. However, in the study, it was impossible to determine the pressure distribution of synovial fluid in the wedge-shaped gap due to experimental limitations. Therefore, average synovial fluid pressure in the gap was determined from a simple calculation of the division of total force by contact area. The average pressure, then, was used for the analysis of cartilage friction. However, fluid pressure generated in the gap is generally nonuniform fashion and the effect of the nonuniform pressure distribution on the biphasic lubrication property has not been determined. Therefore, in the present study, we measured the fluid pressure distribution in the wedge-shaped gap in response to sliding motion using a newly developed experimental apparatus. Then, we performed an analytical study using a poroelastic biphasic model to determine the influence of synovial fluid pressure on the biphasic lubrication property in articular cartilage.

2 Methods

2.1 Measurement of fluid pressure distribution

We developed a friction tester (Fig. 1) to measure the fluid pressure distribution in the wedge-shaped gap in response to sliding motion. The tester was designed so that the lateral side of an acrylic cylinder of 30 mm in diameter and 30 mm of width could be slid against a flat aluminum plate (A5052, arithmetic average roughness $R_a \leq 26$ nm). The space between the cylinder and the plate was filled with silicone oil with a viscosity of 0.1 Pa·s (100CPS, Brookfield Engineering, USA). The oil was selected in reference to the viscosity of human synovial fluid reported by Murakami et al. [17]. The cylinder was slid against the plate at a sliding speed of 1, 15 and 30 mm/s for total sliding distance of 60 mm at room temperature while the contact pressure was kept at 0.06 MPa. The indenter sized for 30 mm and then passed over a pressure sensor (FOP-M Pressure Sensor, FISO Technologies Inc. Canada) embedded in the center of the aluminum plate so that well-developed fluid could be achieved when the indenter passed over the pressure sensor. Fluid pressure generated in the wedge-shaped gap was measured as a function of time at a frequency of 5 kHz using the pressure sensor. Since sliding speed was constant, pressure-time relation was transformed to pressure-position relation for the determination of the pressure distribution in the gap under the assumption of steady-state flow.

2.2 Cartilage model

A fiber-reinforced 2-dimensional poroelastic cartilage model was developed on ABAQUS 6.14 (Dassault Systemes, France) (Fig. 2) in reference to previous studies by Fujie and Imade [9], and Li et al. [18]. The size of cartilage model was 31 mm (length) $\times$ 1.5 mm (thickness), which consisted of poroelastic elements of 25 $\mu$m $\times$ 25 $\mu$m. Each element consisted of a pore pressure, plane strain element (CPE4RP) as an isotropic model of the solid phase of cartilage, and horizontal and vertical oriented spring elements (SPRING A) as a model of collagen fibers. The bottom of the model was perfectly fixed and impermeable. Outflow of water from the side and surface of the model was permitted except contact region.
The material properties of articular cartilage in the models are shown in Table 1. Poisson’s ratio of the solid phase of cartilage was set 0.42 in reference to Li et al. [18]. The coefficient of friction of cartilage to the metal plate in solid-to-solid contact region was set 0.42 in reference to our previous study of friction of cartilage to the metal plate in solid-to-solid contact [19]. Based on following Eq. (1) by Lai and Mow [20], strain-dependent hydraulic permeability, \( k \) was defined, where \( k_s \) represents the initial permeability at no strain, \( M \) represents the permeability coefficient, and \( \varepsilon \) represents the volumetric strain of cartilage matrix. The initial permeability \( k_0 \) and the coefficient \( M \) were determined from the experiment in previous studies [21,22].

\[
k = k_s \exp \left[ M \varepsilon \right]
\]

For calculation in Abaqus, strain was transformed to porosity \( \varepsilon \) using following Eq. (2),

\[
\varepsilon = (\varepsilon - \varepsilon_0) / (1 + \varepsilon_0)
\]

where \( \varepsilon_0 \) represents the initial porosity, defined as the porosity at no strain, and was set 4 because water is incompressible, and its content is approximately 80% in articular cartilage. In analysis, Eqs. (1) and (2) were used to determine the hydraulic permeability of articular cartilage. The moduli of the solid phase of cartilage and collagen fiber were determined through a curve fitting of analytical data to experimental data obtained from an unconfined compression/relaxation test [23]. In the experiment, cylindrical plug-specimens of normal articular cartilage with subchondral bone of 3 mm in diameter and 2 mm in depth were extracted from the bearing surface of the distal femur of immature porcine knee joints. In the unconfined compression test, the specimen surface was made to contact to a flat impermeable aluminum plate. Compressive strain to the specimen was increased to 10% of the specimen thickness for 5s, then strain was kept for 20 minutes for relaxation in physiological saline solution. From the test, a measured stress-relaxation curve was obtained. Subsequently, computational compression/relaxation analysis of the cartilage model was carried out while the moduli of the solid phase and collagen fiber were varied. By means of the curve fitting of analytical data to the experimental data, the moduli of proteoglycan and cartilage were determined. The obtained properties shown in Table 1 were applied to the standard cartilage model.

To determine the effect of synovial fluid pressure on the biphasic lubrication property of articular cartilage, synovial fluid pressure model (SFP model) was established in which the effusion of interstitial fluid from articular cartilage was regulated depending on the pressure difference between the applied fluid pressure and analyzed pressure at each surface element using following Eqs. (3) and (4),

\[
\begin{align*}
  v_n &= k_s (p_n - p_w) \\
  v_n &= 0
\end{align*}
\]

where \( v_n \), \( k_s \), \( p_n \) and \( p_w \) represent the normal vector of pore water flow velocity, permeability of cartilage surface (~ 1), pore pressure of surface element, and synovial fluid pressure. The synovial fluid pressure was determined from the fluid pressure distribution from the experiment described in section 2.1. Pressure distribution data were plotted against the sliding stroke (Fig. 3 (a)), and the pressure data between 25 to 30 mm before the indenter passed over the pin-hole for pressure detection were extracted (Fig. 3 (b)). Pressure data within 5 mm from the pin-hole were discretized at every 25 μm so that the discretized width (25 μm) was coincident with the width of the poroelastic element. Then, the discretized pressure data were substituted to the models as pressure data generated in the wedge-shaped gap (Fig. 3 (c)).

2.3 Friction analysis

Using the developed models of articular cartilage, a friction analysis was performed. A rigid cylindrical indenter (Φ30 mm) was indented to the cartilage surface up to a contact force of 0.1 N (average contact pressure of 0.03 MPa) and the contact force was maintained at 0.1 N for 5 seconds. The indenter was slid over the cartilage surface at a sliding speed of 1, 15 or 30 mm/s for sliding distance of 15 mm. The temporal change of coefficient of dynamic friction at each speed was calculated from the integral of shear stress divided by the integral of contact pressure. Note that since the deformation of cartilage model was small in this contact pressure condition, plowing

![Table 1 Mechanical properties of cartilage models](image)

![Fig. 3 Flow of fluid pressure data processing](image)
friction effect was ignored. The coefficient of dynamic friction was calculated from average values measured between 10 and 15 mm of sliding distance at steady state.

3 Results

Fluid pressure distribution in the wedge-shaped gap sandwiched by confronting articular cartilage surfaces at a sliding speed of 1, 15 and 30 mm/s are shown in Fig. 4. The pressure increased until the indenter passed over the pressure sensor (30 mm point of the sliding distance). The peak pressure were $1.5 \times 10^{-1}$ kPa, $9.6 \times 10^{-1}$ kPa and 3.4 kPa at a speed of 1, 15 and 30 mm/s, respectively. It was found that fluid pressure distribution exists in the wedge-shaped gap and the pressure peak increases with sliding speed.

The temporal changes of calculated coefficients of dynamic friction at 30 mm/s of sliding speed are shown in Fig. 5. The steady state of the calculated coefficient was achieved in 10-15 mm of sliding distance. The coefficients of dynamic friction at each sliding speeds are shown in Fig. 6. In standard model, the coefficients of dynamic friction were 0.069, 0.060, and 0.057 at a sliding speed of 1, 15 and 30 mm/s, respectively. In SFP model, the coefficients of dynamic friction were 0.067, 0.054 and 0.042 at a sliding speed of 1, 15 and 30 mm/s, respectively. The coefficients of dynamic friction in both SFP and standard models decreased with the increase of sliding speed. Note that the coefficients of dynamic friction were smaller in SFP model than in standard model with the largest difference of 25% observed at 30 mm/s. Pore pressure distribution of interstitial fluid in articular cartilage at the sliding speed of 30 mm/s in both standard and SFP model are shown in Fig. 7. Pore pressure was higher in SFP model than in normal model just below the contact area.

![Fig. 4 Fluid pressure distribution in wedge-shaped gap at 1, 15, 30 mm/s of sliding speed](image)

![Fig. 5 Temporal changes of the coefficients of dynamic friction at 30 mm/s of sliding speed](image)

![Fig. 6 Coefficients of dynamic friction of the standard and SFP model at 1, 15, 30 mm/s of sliding speed](image)

![Fig. 7 Pore pressure distribution of the standard and SFP model at 30 mm/s of sliding speed. Right figure: Contours adjusted at the center of the contact area on left figure](image)
4 Discussion

Results revealed that the peak fluid pressure generated in the wedge-shaped gap increased with the increase of sliding speed. Results also revealed that the coefficient of dynamic friction was lower in SFP model than in standard model. Moore et al. indicated that interstitial fluid in articular cartilage was recovered by inflow of water from the wedge-shaped gap, which, in turn, resulted in supporting biphasic lubrication [24]. The effect of hydrodynamic pressure in synovial fluid on the biphasic lubrication was not discussed in their study. Therefore, our previous study is, to our knowledge, the first one that analytically indicates the effect of hydrodynamic pressure in the wedge-shaped gap on the biphasic lubrication property of articular cartilage. And, more precise determination was completed in the present study as compared with our previous study in which fluid pressure distribution in the gap was experimentally measured and its effect on the biphasic lubrication was analyzed. However, there are some limitations that should be noted. In pressure measurement, we used an aluminum plate that is harder than articular cartilage because the pressure sensor had to be stably fixed to the plate. Therefore, we had to choose a low contact pressure condition to minimize contact deformation difference between the experiment and analysis. In addition, pressure-time relation obtained from the friction experiment was transformed to pressure-position relation for the analysis of fluid pressure distribution in the wedge-shaped gap. This is possible only when the fluid flow is in steady state. Therefore, the results obtained in the present study reflect the effect of synovial fluid pressure on the frictional property of synovial joints during a steady-state situation, for example, when a joint moves at the middle of range of motion with a constant speed. It is also a limitation that two-dimensional model was used in the friction analysis in the present study. This might lead to an overestimation of the effect of fluid pressure on suppressing the outflow of interstitial fluid from cartilage. However, the present study is still valuable in tribological research filed because, as we previously mentioned, this is the first one that describes the interaction between hydrodynamic lubrication and biphasic lubrication. Moreover, the interaction may still play an important role in joint lubrication at other loading conditions depending on articular surface geometry, phase of gait, and so on.

Results revealed that the coefficient of dynamic friction in SFP model was decreased for 8.7% at 15 mm/s of friction speed, and for 26% at 30 mm/s of friction speed as compared with those in standard model. Flow rate vectors in normal direction to cartilage model surface at a sliding speed of 30 mm/s are shown in Fig. 8. Flow rate vectors near the contact region are smaller in SFP model than in standard model, in particular near the tip-end of wedge-shape gap. The decrease of flow rate in normal direction means that fluid pressure outside cartilage suppressed the outflow of interstitial fluid from cartilage and finally resulted in pore pressure increase in articular cartilage in SFP model (Fig. 7). Note that regulation of fluid outflow in only 5 mm in length in the gap led to 26% decrease in the coefficient of dynamic friction of articular cartilage at a friction speed of 30 mm/s. It was impossible to deal with fluid inflow into cartilage from outside in the simulation, although the fluid pressure was higher outside than inside near the tip-end. It is suggested that the decrease in the coefficient of dynamic friction would be more than 26% if the inflow is taken into consideration.

In our previous study [16], fluid pressure outside cartilage was assumed to be uniform, and its effect on the biphasic lubrication property was investigated. To confirm the value of the present study in comparison with the previous study, an average pressure was calculated from the pressure distribution measured in the present study, and it turned out be 113 Pa at a sliding speed of 30 mm/s. By substituting the average pressure to \( p_w^{\infty} \) in Eq. (3), the coefficient of dynamic friction was calculated.
at 0.055. This coefficient of dynamic friction calculated under the assumption of uniform pressure distribution is higher than that (0.042) calculated under the assumption of nonuniform pressure distribution in SPF model in the present study. This indicates that higher fluid pressure applied near the tip-end of the wedge-shaped gap is more effective for decreasing the coefficient of dynamic friction.

The biphasic lubrication of articular cartilage has been wildly investigated by many research groups including our group [8-13]. In those studies, many crucial factors for improving the biphasic lubrication property have been reported, such as migration of contact area along the articular surfaces [8], low tangential permeability of superficial layer in articular cartilage [9], reinforcement of solid phase in articular cartilage by collagen network [10,11], surface amorphous layer of articular cartilage [13] and so on. The present study implies that synovial fluid pressure in the wedge-shaped gap is also a candidate for the crucial factors. Moreover, the squeeze film effect is known to play a more important role than wedge film effect for hydrodynamic joint lubrication, because of cyclic loading and low sliding speed during articular motion [25]. The influence of hydrodynamic fluid pressure derived from squeeze film effect on the biphasic lubrication property will be further investigated in future works.

5 Conclusion

We performed experimental and analytical studies on the effect of hydrodynamic fluid pressure generated in the wedge-shaped gap between confronting cartilage on biphasic lubrication property in articular cartilage. It is suggested that synovial fluid plays important roles not only in wedge-film hydrodynamic lubrication but also in biphasic lubrication by suppressing the effusion of interstitial fluid.

Acknowledgments

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References


