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Effects of low tangential permeability in the superficial layer on the frictional property of articular cartilage

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Abstract

The biphasic characteristics of articular cartilage are known to play important roles in cartilage lubrication. However, it is still difficult to biotribologically explain the extremely low friction coefficient observed in articular cartilage. Previous studies have indicated that the surface layer of articular cartilage includes tangentaill-aligned dense collagen fibers while permeability of articular cartilage in tangential direction is dramatically reduced in response to compressive strain. Therefore, we hypothesized that the anisotropic structure and property in articular cartilage surface improve the lubrication and frictional properties. A fiber–reinforced poroelastic biphasic model was developed in Abaqus to determine the effect of low tangential permeability on the frictional property of articular cartilage. In the model, the tangential permeability in the superficial layer of 100 μm in thickness was reduced to 1/10 as compared with normal permeability. Results revealed that the permeability-reduced superficial layer plays an important role in decreasing friction coefficient in articular cartilage and the role is more significant in slower friction including the start-up friction. Results also revealed that there is a positive effect of the thickness of the low permeability layer on the start-up friction property, while the effect was almost negligible on the dynamic friction property.

Keywords: Articular cartilage; Superficial layer; Anisotropic permeability; Frictional property; Fiber–reinforced poroelastic biphasic model

1. Introduction

Articular cartilage has a significant lubrication property that has been explained in previous studies by many lubrication theories including boundary lubrication [1,2], hydrodynamic lubrication [3–7], mixed lubrication, surface gel hydration lubrication [8], biphasic theory [9,10], and so on. In the last couple of decades, many investigators have focused on biphasic theory for the consideration of the lubrication mechanism of articular cartilage. This theory, originally developed by Mow et al. [9], describes that both solid and fluid phases play roles in resisting to externally applied compressive loads to articular cartilage. With articular motion, friction force is kept low because of negligible friction occurred in fluid phase that bears the most of the applied load. Such biphasic nature of articular cartilage results in a significant role in reducing friction and enhancing lubrication. Recently, the friction property of articular cartilage has been well explained with the biphasic theory by Ateshian [11], and Caligaris and Ateshian [12]. They found that interstitial fluid pressurization in response to articular motion bears the applied load in transient or steady-state conditions. Meanwhile, Reynaud and Quinn indicated that the hydraulic permeability was significantly anisotropic; the tangential permeability, defined as the permeability in direction parallel with cartilage surface, becomes lower than the normal permeability, defined as the permeability in direction normal to cartilage surface, under compression [13]. They reported that tangential permeability becomes 1/10 of normal permeability under 30% of compressive strain. This unique nature of anisotropic permeability in articular cartilage may be related to a morphological finding; the superficial layer of articular surface was consisted of close-packed collagen fibers aligning parallel with articular surface and tangling each other (Fig. 1)[14]. It is, therefore, considered that the hydraulic permeability of the

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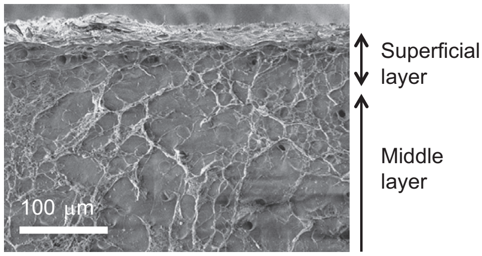

Fig. 1. Scanning electron microscopic observation of a cross section of articular cartilage from a porcine distal femur.

superficial layer is extremely low in tangential direction under compressive strain, although the superficial layer is so thin that the tangential permeability cannot be measured. Based on these previous findings and consideration, we have a hypothesis that the unique structure and anisotropic properties in the articular cartilage superficial layer may improve the biphasic lubrication properties. In fact, McCutchen hypothesized that anisotropic hydraulic permeability under compression plays important roles in lubrication property in articular cartilage [5]. However, no quantitative study has been performed as regard with the effect of anisotropic hydraulic permeability on the frictional property in articular cartilage. Therefore, we performed an analytical study using a fiber–reinforced poroelastic biphasic model to determine the effect of low tangential permeability in the superficial layer on the frictional property of articular cartilage.

2. Materials and method

2.1. Development of analytical models

A fiber–reinforced 2-demensional poroelastic cartilage model was developed on Abaqus 6.11 (Dassault Systemes, US) (Fig. 2), while referring from a previous study by Li et al. [15] and Sakai et al. [16]. Cartilage of $8 \times 1.5\ \mathrm{mm}^2$ was assumed to consist of fiber–reinforced poroelastic elements of $25 \times 25\ \mu\mathrm{m}^2$. Each element consisted of a pore pressure, plane strain element (CPE4RP) as a model of the solid phase of cartilage without collagen fibers, and laterally oriented spring elements (SPRING A) as a model of collagen fibers. The material properties of articular cartilage in the models were determined as follows. First, the permeability of cartilage was obtained from our previous experimental study [17] and was substituted to that of the solid phase of cartilage (without collagen fibers). Cylindrical plug-specimens of normal articular cartilage with subchondral bone of 4 mm in diameter and 4–6 mm in depth were extracted from the bearing surface of the distal femur of mature porcine knee joints. From the plug-specimens, layer-specimens of superficial, middle, and deep layers of 250–300 μm in thickness were sliced and sandwiched by polyethylene filters (X-4741, Porex Technologies, USA) in an unconfined permeability tester developed in our laboratory [18] (Fig. 3). Note that the tester is similar in principle to that developed by Weiss and Maakestad [19]; the outflow from the lateral side of cartilage layer-specimens is sealed with an O-ring (PP50-6, San-ei-suisen, Japan), while uniaxial compressive strain of the layer-specimens is controlled with a servo-

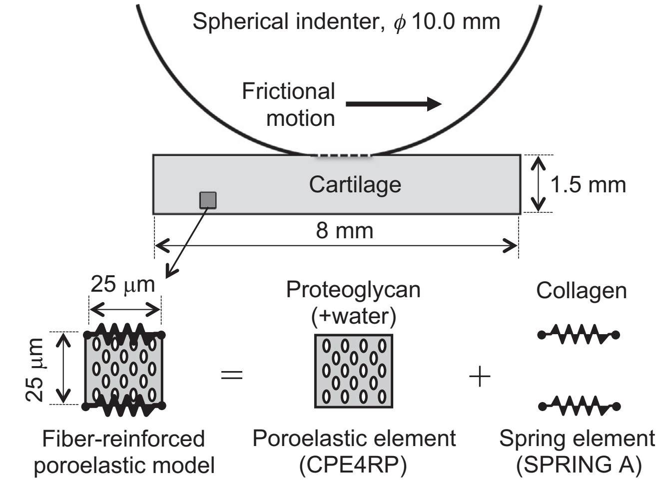

Fig. 2. Fiber–reinforced poroelastic model of articular cartilage in contact with a metal sphere of 10 mm in diameter.

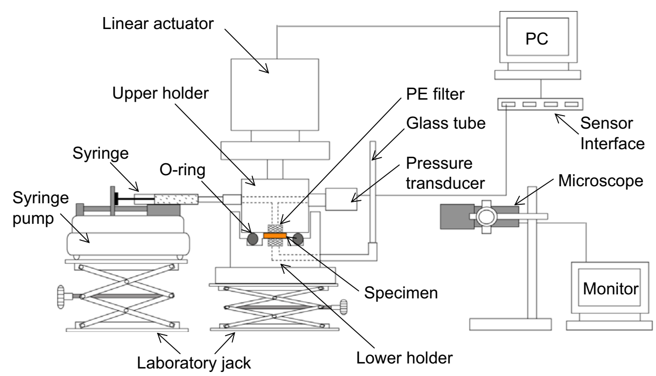

Fig. 3. Custom-made permeability tester for articular cartilage.

motor (LAH-46-3002-F-SP, Harmonic Drive Systems, Japan). The area of specimen exposed to flow was 1 mm in diameter. With fluid pressure of 70 kPa applied to the layer-specimen with a syringe pump (KDS-101, KD Scientific, USA), the rate of water permeated through the specimen was measured by waterhead and permeability was calculated based on Darcy's law [20]. Results revealed that the normal permeability of the superficial, middle, and deep layers were $1.03 \times 10^{-15}\ \mathrm{m}^4/\mathrm{Ns}$, $1.10 \times 10^{-15}\ \mathrm{m}^4/\mathrm{Ns}$, and $0.86 \times 10^{-15}\ \mathrm{m}^4/\mathrm{Ns}$, respectively, at 30% of compressive strain, with no significant difference observed among the layers. These measured data were, therefore, averaged to $1.0 \times 10^{-15}\ \mathrm{m}^4/\mathrm{Ns}$ for the permeability of overall cartilage under 30% of compressive strain, k. Initial permeability k_0, defined as permeability under no strain, was determined based on following equation by Lai and Mow [21], where k represents the permeability measured under volumetric strain, ε, and M represents permeability coefficient.

$$k = k_0 \exp[Me] \quad (1)$$

The coefficient, M, was determined as the inclination of the permeability-strain logarithmic relationship obtained from porcine cartilage middle layer-specimens in our previous study [17] (Table 1), and was set 2.64 in the present study. For calculation in Abaqus, strain was transformed to porosity, e,