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Correlation between friction of articular cartilage and reflectance intensity from superficial images

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Abstract

The lubrication mechanism of articular cartilage is characterized by an efficient performance. In this work, friction of articular cartilage was evaluated with in-site images of articular surface. The images were captured with the laser light reflected at the interface between a prism and articular cartilage. The attenuation of reflectance was associated with the increase of the contact of collagen network of articular cartilage. The light reflectance and friction coefficient for short sliding presented a significant positive correlation. Friction tests were also carried out for short (30 s) and long (300 s) preloading times. The results indicate that depletion of fluid film is responsible for the increase of friction and the recovery of the fluid film was observed for the long preloading after the early stage of sliding.

Keywords: Articular cartilage; Friction; Reflectance; Preloading

1. Introduction

Articular cartilage is the bearing surface of synovial joints and is characterized by a superb mode of lubrication [1,2]. Several approaches have been used in order to elucidate the mechanism of lubrication of the articular cartilage [3–6], and some researchers consider that the articular surface plays an important role on the lubrication [7–11]. However, the evaluation of articular surface has presented considerable difficulties mainly due to the high contents of water (60–80% of wet weight) of the articular cartilage [12,13]. The presence of water is an obstacle for the comprehension of this mechanism because it makes the acquisition of images difficult which assist in the evaluation of the articular surface. Conventional techniques, such as a scanning electronic microscopy (SEM), do not allow an efficient analysis of the articular surface because they require the dehydration of specimens, which changes the natural characteristics of articular cartilage. In addition, it is very difficult to perform the analysis of articular surface and friction tests simultaneously.

In this work, a technique based on the frustrated total internal reflection (FTIR) is presented to acquire the images of the articular surface during friction tests. In this technique, variations of the reflectance (ratio between the reflected and incident light intensities) are associated with the changes that occur at the articular surface. One advantage of this technique is that the acquisition of images and the friction test can be realized simultaneously in aqueous environment. This work presents the first results using this technique and the effect of the preloading time on the friction coefficient of articular cartilage was evaluated.

1.1. Background

FTIR occurs due to a perturbation of the evanescent waves (EWs) field that is formed at an interface between two different mediums (1 and 2) where a light beam undergoes total internal reflection (TIR) [14] as shown in Fig. 1a. TIR occurs when the medium, where the light is

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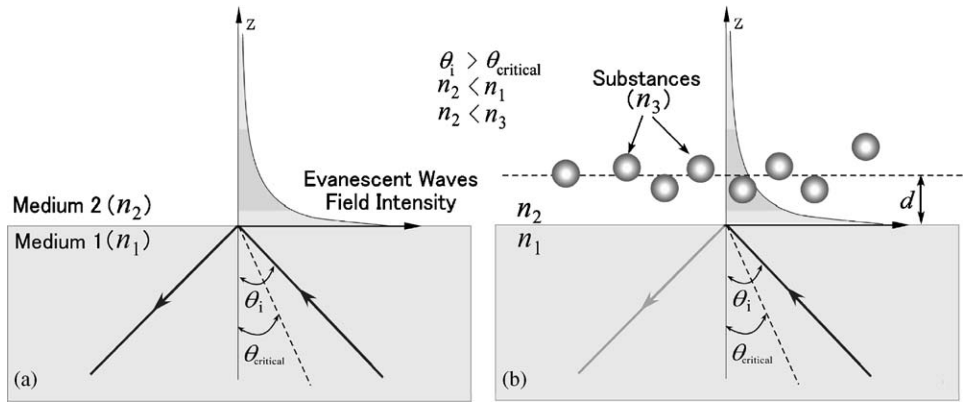

Fig. 1. (a) Total internal reflection and (b) frustrated total internal reflection. n_i represents the refractive index of medium i, θ_i is the angle of incidence, $\theta_{critical}$ is the critical angle and δ is the thickness of the gap between mediums 1 and 3.

derived (medium 1), has a refractive index (n_1) larger than that of the other medium (n_2), and the angle of incidence (θ_i) is larger than the critical angle ($\theta_{critical}$). The critical angle is calculated using the following equation:

$$\theta_{critical} = \sin^{-1}\left(\frac{n_1}{n_2}\right). \tag{1}$$

EWs are a kind of electromagnetic waves that propagate from the place where the light is reflected and decreases exponentially as the distance from the interface increases. Albeit average of the energy transported by EWs is zero, substances placed near the interface (substances with refractive index of n_3, in Fig. 1b) can perturb the evanescent field and attenuation in the reflected light can be observed (Fig. 1b), in spite of occurrence of TIR [15]. A minimal gap (δ) between the mediums 1 and 3 is necessary for the frustration of TIR and the penetration depth of EWs limits the thickness of this gap, which is found in the nanometers order for visible light [16]. In addition, the refractive index of this gap (n_2) must be lower than the refractive indices below and above this gap (n_1 and n_3, respectively). When these two conditions are assured, the FTIR occurs, which is characterized by the attenuation of the reflected light intensity (Fig. 1b). Furthermore, FTIR can also occur due to the alterations in the refractive index of medium 2. The theoretical equations of the reflectance for p-polarized (parallel to the plane of incidence) and s-polarized (normal to the plane of incidence) lights are, respectively,

$$R_p = \left(\frac{\cos\theta - \sqrt{(n_2/n_1)^2 - \sin^2\theta}}{\cos\theta + \sqrt{(n_2/n_1)^2 - \sin^2\theta}}\right)^2 \tag{2}$$

and

$$R_s = \left(\frac{(n_2/n_1)^2\cos\theta - \sqrt{(n_2/n_1)^2 - \sin^2\theta}}{(n_2/n_1)^2\cos\theta + \sqrt{(n_2/n_1)^2 - \sin^2\theta}}\right)^2, \tag{3}$$

where n_1 and n_2 are the refractive indices of mediums 1 and 2 (Fig. 1), respectively; θ is the angle of incidence.

In Fig. 2, the reflectance intensity is plotted in relation to the refractive index of the medium 2. The refractive index of medium 1 is 1.515 (glass BK-7) and the angle of incidence is 64.8°. In accordance with this graph, a significant increase in the refractive index can frustrate the occurrence of the TIR.

Whereas the refractive index can change for each kind of substance, the attenuation of reflectance due to the placement of articular cartilage at the interface can be used as an important parameter for the recognition of substances present at the articular surface. FTIR can occur when the solid phase of articular cartilage is in contact to the interface because the refractive index of collagen (between 1.37 and 1.55) [17] is larger than that of the usual physiological mediums (e.g., saline with refractive index of 1.34). Collagen network corresponds to about 20% of wet weight of articular cartilage [12].

Thus, the reflectance of incident light at the articular surface can provide relevant information about the superficial condition of articular cartilage. An important advantage of this method is that the variations of the reflectance are limited to the articular surface because the sensitivity of EWs is obtained in the order of nanometers from the contact. Moreover, the refractive index of the solid part of articular cartilage (collagen network) is sufficiently large to frustrate the TIR.

2. Experimental details

2.1. Materials

The specimens were harvested from the lateral femoral condyles of matured and healthy (about 100 kg) pigs with a biopsy punch with 5 mm of diameter and the mean thickness of articular cartilage was about 1.4 mm. The small diameter of specimens aimed to avoid the effect of the curvature of femoral condyles of pigs. In addition, the experimental apparatus that was used in this work was