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The Frictional Coefficient of Bovine Knee Articular Cartilage

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Abstract

The normal displacement of articular cartilage was measured under load and in sliding, and the coefficient of friction during sliding was measured using a UMT-2 Multi-Specimen Test System. The maximum normal displacement under load and the start-up frictional coefficient have similar tendency of variation with loading time. The sliding speed does not significantly influence the frictional coefficient of articular cartilage.

Keywords: articular cartilage, normal displacement, coefficient of start-up friction

1 Introduction

Cartilage has excellent biomechanical and tribological properties with low friction and minimum wear in diarthrodial joints throughout the lifetime of most people, and the lifetime of articular cartilage can be 40 years or longer. This has inspired material and bionic scientists to study the mechanism of such excellent tribological characteristics in order to develop artificial joints. Various mechanisms have been proposed to explain the remarkable low friction behavior of articular cartilage, such as fluid film, mixed and boundary lubrication. In the fluid film lubrication regime, both cartilage surfaces are completely separated by a layer of synovial fluid, which results in minimal friction[1, 2]. However, this lubrication theory fails to explain the low friction in sensorial joints under conditions of little motion such as start-up after a long period of standing. Therefore, various mixed lubrication mechanisms have also been proposed, including boosted lubrication[3], weeping lubrication[4] and biphasic lubrication[5]. In particular, the load carried by the fluid phase in articular cartilage is responsible for low friction, and the loading time prior to sliding is an important factor[6–8]. In addition to these mixed lubrication theories, boundary lubrication is extremely important in ensuring low friction and protecting the surfaces when two cartilages are in direct contact[9].

In this study we investigate the frictional behaviour of articular cartilage of bovine knee with mixed/boundary lubrication regimes in bovine serum, by measuring normal displacement under load and the coefficient of friction after periods of stationary loading varying from 5 sec to 60 min. The influence of sliding speed upon friction is also investigated.

2 Materials and methods

2.1 Materials

Articular cartilages were collected from bovine femoral condyles and from the moral-patella articulating surfaces, with the underlying subchondral and cancellous bone retained, then were cut to the square form of 7 mm×7 mm bone and rectangular form of 30 mm×10 mm bone which were called upper cartilage and lower cartilage respectively. The average thickness of the cartilage layer was 1.3 mm, and that of subchondral bone was 2 mm. The surface of cartilage was kept horizontal by polishing the underside of the underlying subchondral bone, so as to ensure that the contact areas were horizontal on all specimens. Articular cartilage specimens were stored frozen at −20 ℃ in saline. Prior to the tests the cartilage specimens were defrosted and immersed in

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bovine serum for at least one hour before use.

Bovine serum with concentration of 99% was bought from Jianghai Bioengineering Limited Company of Heilongjiang Province. A UMT-2 Multi-Specimen Test System was used to measure the normal deformation, tangential force, normal force and sliding length simultaneously.

2.2 Methods

2.2.1 Normal displacement test under load

A loading test was carried out to investigate the normal displacement of cartilages under load. The upper cartilage was stuck to a stiff 8 mm×8 mm metal fixture, and the fixture was connected to the tool holder of the Test System with a pin. The tool holder, pin and fixture were in line. The lower cartilage was fixed to the bottom of a bath made of Ultra High Molecular Weight Polyethylene (UHMWP) filled with bovine serum (Fig. 1). When the two cartilages contacted, a strain gauge measured changes in the Z-carriage caused by the displacement of the cartilages. The upper cartilage was loaded to 40 N under programmed control, and the computer automatically recorded the displacement. Normal displacement was the total displacement of upper and lower cartilages. Loading time ranged from 5 sec to 60 min.

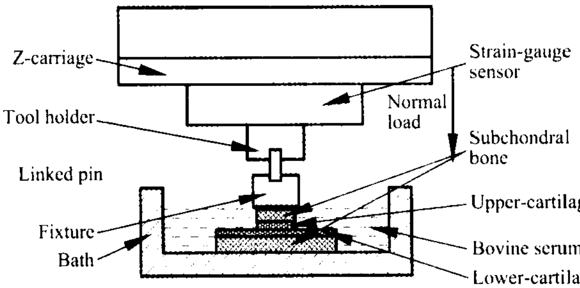


Fig. 1 Experimental methods of loading test of articular cartilage.

2.2.2 Frictional test in sliding

Sliding tests were carried out to investigate the frictional behavior of cartilages in sliding. Prior to sliding test, the cartilage was loaded vertically. When the upper cartilage was sliding the lower cartilage remained at rest (Fig. 2). The friction force in sliding direction (F_x) and the normal force (F_z) were measured by force transducers in the test system. The frictional coefficient was calculated as F_x/F_z. The sliding was in one direction and at a constant speed. Each loading and sliding test was controlled by computer. The normal load of 40 N applied to the upper cartilage produced a stress in the range of 0.5 MPa to 4 MPa (depending on the contact area) representative of physiological loading. Lower sliding speeds were employed to ensure that the contact operated in mixed or boundary lubrication[9]. Different sliding speeds were used to investigate their influence on frictional behavior of the articular cartilages. After the sliding test the cartilages were unloaded and immersed in bovine serum for several minutes allowing them to rehydrate again and to recover their former structure. The time for which the cartilage was unloaded and immersed in bovine serum was twice that under load.

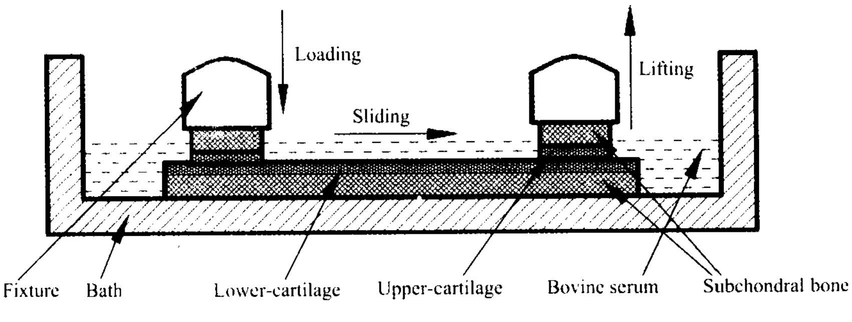


Fig.2 Experimental methods of sliding test of articular cartilage.

The experiments were conducted with loading times of 5 sec, 30 sec, 1 min, 2 min, 4 min, 7 min, 12 min, 20 min, 30 min, 45 min and 60 min, and under sliding speeds of 2 mm·s^{-1}, 4 mm·s^{-1} and 7 mm·s^{-1} respectively. The sliding distances were 10 mm, 12 mm and 14 mm, respectively. Each experiment was repeated three times under the same condition, hence 11×3×3 experiments were performed. The normal displacement and the coefficient of friction were the mean value of three experiments.

3 Experiment results

3.1 Normal displacement

Fig. 3 shows the normal displacement as function of the loading time. The normal displacement initially ascended sharply, and then rose slowly after about 12 min. Fig. 3 shows that the repeatability of experiments is good, that the articular cartilage has good deformation recovery, and that the normal displacement depends strongly on the loading time. Fig. 4 shows how the normal displacement varies with loading time. The slope initially declines sharply, and decreases slowly after about 12 min. Regression analysis gives the relationship between normal displacement and loading time as

$$s = \frac{1}{0.392 + 2.51t^{-0.5}} \quad (t > 0)\,, \qquad (1)$$

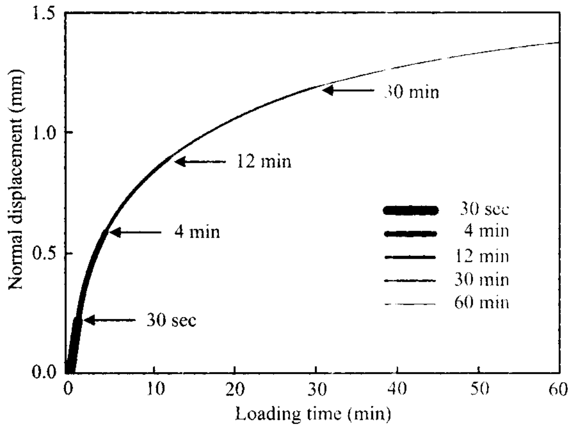


Fig. 3 The normal displacement as function of loading time.

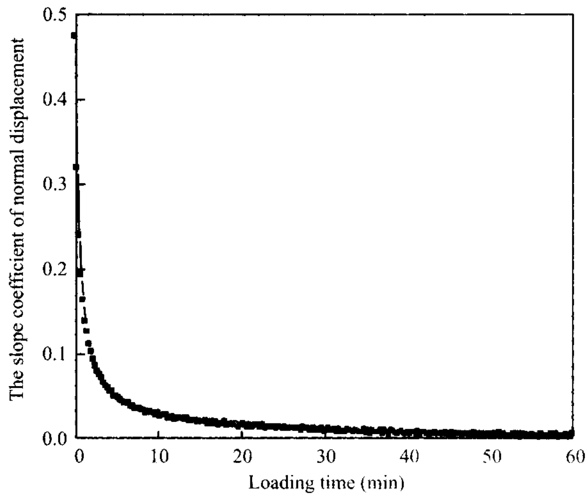


Fig. 4 The slope coefficient of normal displacement varied with loading time.

where s is normal displacement and t loading time. Fig. 5 shows excellent agreement of Eq. (1) with experimental results. Therefore, Eq. (1) can describe normal displacement of articular cartilage with loading time.

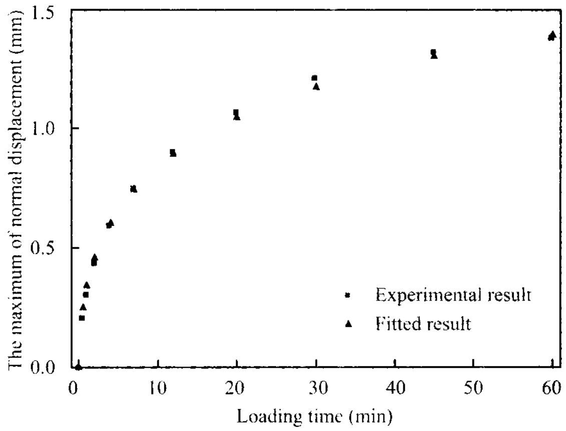


Fig. 5 Comparison of maximums of normal displacement and fitted results under different loading times.

3.2 Frictional coefficient

Fig. 6 shows how the coefficient of friction varied with sliding speed when the loading time was 5 sec. The coefficient of friction initially ascended sharply, descended slowly and ascended slowly. The influence of sliding speed on the coefficient of friction is insignificant. These results indicate that the articular cartilage was in the boundary or mixed lubrication regimes when loading time was 5 sec. It can be speculated that, with loading time between 5 sec and 60 min, articular cartilages were all in the boundary or mixed lubrication regimes.

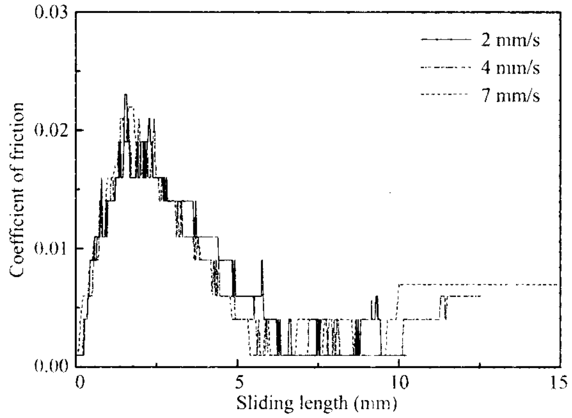


Fig. 6 The coefficient of friction as function of sliding length with different sliding speeds, loading time was 5 sec.

Fig. 7 shows the coefficient of friction and normal displacement as functions of sliding time, in which the sliding speed was 4 mm·s^{-1} and loading time was 4 min. We can divide the coefficient of friction into four stages, in stage 1 from *a* to *b*, the coefficient ascended sharply; in stage 2 from *b* to *c*, the coefficient declined sharply; in stage 3 from *c* to *d*, the coefficient descended slowly; in the stage 4 from *d* to *e*, the coefficient rose slowly. The coefficient approached its maximal value at point *b*, which is called the coefficient of start-up friction. We can also divide the normal displacement into four stages, in stage 1 from *u* to *v*, normal displacement stayed constant; in stage 2 from *v* to *w*, normal displacement descended slightly; in stage 3 from *w* to *x*, normal displacement declined sharply, and the upper cartilage slid up the slope of lower cartilage's groove, therefore, this stage is also referred to as the climbing stage; in stage 4 from *x* to *y*, normal displacement rose slowly.

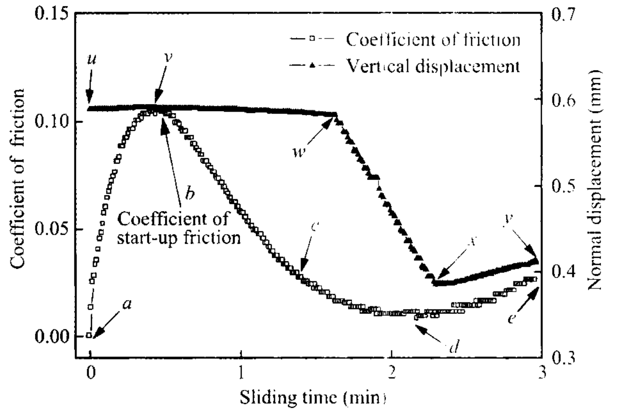


Fig. 7 The coefficient of friction and normal displacement varying with sliding time, the sliding speed was 4 mm·s^{-1} and loading time was 4 min.

Fig. 8 shows coefficient of start-up friction as function of loading time when the sliding speed was 4 mm/s. The coefficient initially ascended sharply, and rose tardily after about 12 min. Thereby, we can obtain the relationship between coefficient of start-up friction and loading time as

$$\mu_m = \frac{1}{0.455 + 20.090\ t^{-0.5}} \quad (t > 0), \qquad (2)$$

where μ_m is the coefficient of start-up friction and *t* loading time. Eq. (2) is also plotted on Fig. 8, which shows excellent agreement with the experimental results. Comparing Eq. (1) and Eq. (2), we may speculate that the coefficient of start-up friction is probably influenced by normal displacements prior to sliding, and the maximum normal displacement may be used to quantify the coefficient of start-up friction.

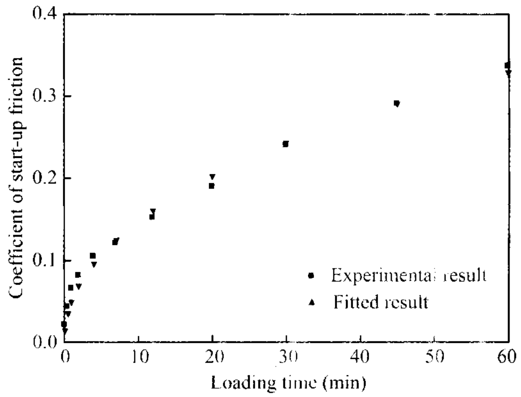
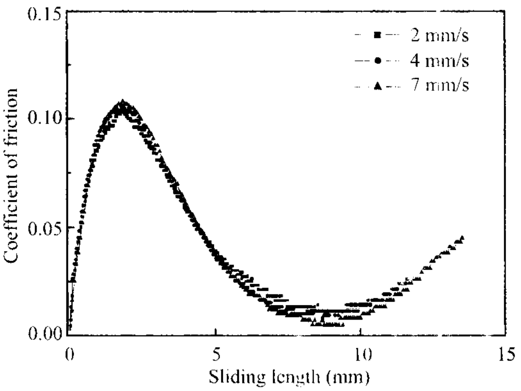


Fig. 8 The coefficient of start-up friction and fitted results varying with loading time, sliding speed was 4 mm·s^{-1}.

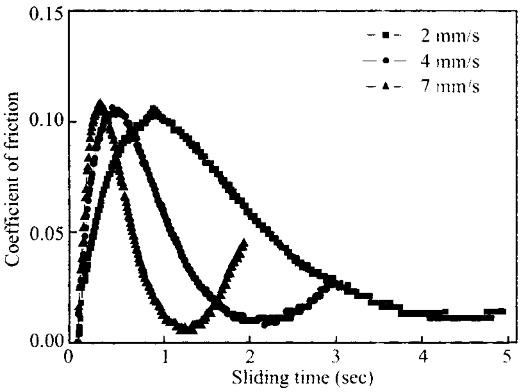
3.3 Frictional property influenced by sliding speeds

Fig. 9a shows the relationship between the coefficient of friction and sliding length, and Fig. 9b shows the relationship between coefficient of friction and sliding time with different sliding speeds and a loading time of 4 min. The trend of change of the coefficient is similar to that in Fig. 6 and Fig. 7. The sliding speed has almost no influence on the coefficient of start-up friction. At sliding speeds of 2, 4 and 7 mm·s^{-1}, the coefficient of start-up friction was 0.107, 0.106 and 0.107, respectively. However, the higher the sliding speeds, the less the time was achieving the coefficient of start-up friction. We may conclude that sliding speed does not significantly influence the frictional coefficient of articular cartilage.



(a) The coefficient of friction as function of sliding length

Fig. 9 The coefficient of friction as function of sliding length and sliding time.



(b) The coefficient of friction as function of sliding time

Fig. 9 Continued.

4 Discussion

Articular cartilage is composed of a network of fine collagen fibrils within which a network of hydrophilic proteoglycan aggregate molecules is immobilized and restrained. Collagen fibrils and proteoglycans are the structural components transmitting the internal mechanical stresses resulted from the loads applied to the cartilage. The structural components, together with water, determine the mechanical behavior of this tissue [10]. For this reason, it was often modeled as a biphasic material [11].

In loading, normal displacement could be referred as an indication of the fluid flow in the cartilage and the load carried by the fluid phase. An initial instantaneous elastic deformation in response to load was primarily due to the change in shape of the cartilage. At this point the fluid flow reached its maximum and the fluid phase carried the largest portion of the load. As the loading time increased, the slope of normal displacement with loading time decreased (Fig. 4). As the rate of flow of fluid in the cartilage declined, the load carried by the fluid phase decreased and the load carried by the solid phase increased. At 45–60 min the contact between upper cartilage and lower cartilage was close to equilibrium, if little further deformation occurred then the load carried by the fluid was close to zero. Thus, normal displacement is significantly affected by loading time. These results are consistent with previous studies [6, 9]. Of course, it is easy to understand that normal displacement functioned in a passive correlation with the load carried by the solid phase. After an equal period of load removal to that of previous loading, the loading test produced a similar displacement when reloaded, indicating a full recovery of fluid content (Fig. 3). This is consistent with previous studies [12]. This shows conclusively that articular cartilage is viscoelastic and can recover automatically under certain conditions.

On initial loading, a large amount of the load is carried by the fluid phase of the cartilage. As the static loading time increases, the load carried by the solid phase increases and that carried by the fluid phase decreases. Hence, the overall frictional force increases which can be simply expressed as

$$F_T(t) = \mu_T(t)W, \tag{3}$$

where $F_T(t)$ is overall friction force, $\mu_T(t)$ overall or aggregate friction coefficient, and W total load. As analysed above, the load W carried by the cartilage is composed of two parts carried by the solid phase and by the fluid phase, when Eq. (3) can be rewritten as

$$F_T(t) = \mu_s(t)\, W_s(t) + \mu_f(t) W_f(t), \tag{4}$$

where μ_s is the effective coefficient of friction attributed to the solid phase, μ_f is the effective coefficient of friction attributed to the fluid phase, $W_s(t)$ is the load carried by the solid phase and $W_f(t)$ is the load carried by the fluid phase. Since μ_s is significantly greater than μ_f, the second term of Eq. (4) can be ignored and we have

$$F_T(t) = \mu_s(t)\, W_s(t). \tag{5}$$

Eq. (5) indicates that the frictional force is mainly determined by the load carried by the solid phase. According to the conclusion above, the friction force is mainly associated with normal displacement under load. When the total load W is a fixed value, the coefficient of friction is also related to normal displacement.

Prior to initial sliding, the upper cartilage is loaded upon the lower cartilage, and the deformed area of lower cartilage is larger than the contacted area of upper cartilage. Of course, the deformation of the area around the contact of the lower cartilage is less than the contacted area, and was strongly related to loading time. Fig. 10 sketches the dynamic variations of the normal displacement of upper cartilage and lower cartilage with sliding length.

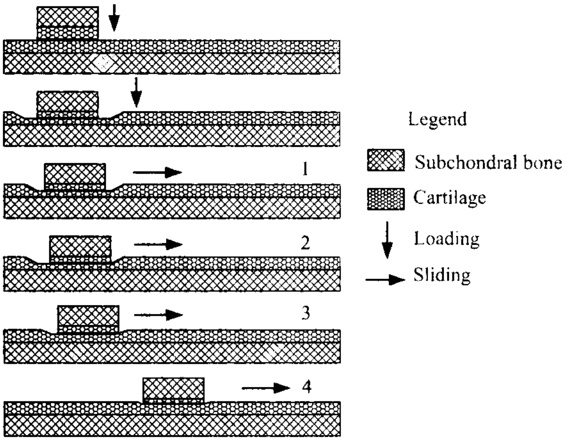


Fig. 10 Normal displacements of upper cartilage and lower cartilage dynamically vary with sliding length.

In stage 1, the coefficient ascended sharply in a short period. At initial instantaneous sliding, the normal displacement was maximum, and the load carried by the solid was also maximum. The coefficient of friction ascended rapidly from zero, and shortly arrived at the maximum. The result is in agreement with previous studies [13]. Normal displacement kept almost unchanged, which showed the upper cartilage just started to slide.

In stage 2, the coefficient of friction declined sharply. When the upper cartilage slid on the surrounding area of lower cartilage, the load carried by the solid in this area was obviously less than that on the contact area, which made the coefficient of friction reduce quickly. Normal displacement went down slightly, which showed the upper cartilage was on the surrounding area of lower cartilage.

In stage 3, the coefficient of friction reduced slowly. When the upper cartilage passed through the circumjacent area of lower cartilage, it bore the trend of climbing up the slope of the lower cartilage's groove, starting at point w and ending at the point x, which caused a sharp reduction of normal displacement. But the load carried by the solid phase did not decline rapidly.

In stage 4, the coefficient of friction ascended slowly. When the upper cartilage completely passed through the slope of the groove in the lower cartilage, normal displacement of the upper cartilage was larger than that of the lower cartilage, because the lower cartilage was not completely loaded. In the following sliding, the upper cartilage transmitted compressive stress to the lower cartilage, which resulted in increase of load carried by the lower cartilage. Normal displacement then began to ascend slowly until the sliding stopped.

5 Conclusions

The frictional behaviour of articular cartilage of the bovine knee with mixed/boundary lubrication regimes in bovine serum has been studied by measuring the normal displacement under load and the coefficient of friction during sliding. The articular cartilage is highly viscoelastic and is able to recover fully after the load is released. Prior to sliding, the coefficient of start-up friction is mainly determined by the normal displacement, and they have the similar tendency of variation with loading time. The sliding speed does not significantly influence frictional coefficient of the articular cartilage. The results of this study can be used as useful information in the development of bionic joints.

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