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Biotribology behavior and fluid load support of PVA/HA composite hydrogel as artificial cartilage

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ABSTRACT

The human body joint motion is very complicated, which mainly includes sliding, swing, rotation. Therefore, cartilage covering the joint surface bears the repeated friction which is caused by the different movements during the whole life. So sliding, swing and torsion friction behavior of hydrogels need to be researched as synthetic articular cartilage. In this paper, PVA/HA composite hydrogel is cross-linked on the UHMWPE surface through chemical grafting and freezing-thawing method. Biotribology behavior and fluid load support are researched. The results show that swing and torsion friction coefficients are negligibly small, while sliding friction coefficient is largest. There is a negative linear relationship between fluid load support and friction coefficient. Fluid load supports are relative high under swing and torsion friction, so the swing and torsion friction coefficients are relative low. Hydrogel can be replenished by re-swelling to sustain the fluid pressurization during friction under lubrication condition. Both fluid load support and biphasic lubrication due to its porous structure with large amount of water contribute to the low friction coefficient.

1. Introduction

The hip and knee joint are the main load-bearing joints in human body, and they are the main movement parts of human body [1–3]. The basic daily movements of hip joint are flexion-extension, adduction-abduction, internal and external rotation and circumduction. The basic daily movements of knee joint are flexion-extension, adduction-abduction, internal and external rotation and horizontal migration of front and back. So human can complete all kinds of action because of the existing movement of hip and knee joints. The joints are the largest load bearing biological friction pairs. Therefore, cartilage covering the joint surface bears the repeated friction which is caused by the different movements during the whole life. Hence, the articular cartilage wears and fails, which causes the symptom of pain, swelling and bone crepitus. Finally, osteoarthritis is generated [4–9]. Nowadays, the osteoarthritis which is caused by the wear of articular cartilage has become the first disabling disease around the world. About 400 million people suffer the joint disease. Due to limit of the self-repair ability, it cannot repair along once the damage or disease is caused. Therefore, the replace of artificial joint is set to rebuild the joint characteristic [10].

The artificial joint replacement has become the effective way to treat the joint disease or trauma. However, due to the lack of the nature metabolism of artificial implant materials, the compatibility of prosthesis interface and life medium is poor. Moreover, the contact interface of total joint replacement implants is hard-face to hard-face, and the contact surface exists wear. A large number of clinical medical research has confirmed that the wear of artificial joints is the main reason of the aseptic loosening of joint replacement. The local osteolysis which is caused by wear particles leads to the aseptic loosening. This is the main reason of failure of artificial joint replacement [11–13].

Polyvinyl alcohol (PVA) hydrogel has three-dimensional network structure, which is similar to the natural articular cartilage. Meanwhile, it possesses the properties of solid and liquid and it also has a good biocompatibility, mechanical property and biological tribology performance. Recent years, PVA hydrogel is expected to become the cartilage repair material and replace the biological materials [14].

As the human body joints have many movement modes, the research on the friction properties under different movement modes is very important. Researchers researches mainly on tangential sliding friction and wear behavior of the hydrogel [15–18]. Besides, few researches study the flexion-extension (swing) and adduction-abduction (rotation) of the hip and knee joints. Therefore, it is important to study and understand the biological tribology behavior and lubrication mechanism under different movement modes. This paper studies the friction properties and

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fluid load support of PVA/HA composite hydrogel under different movement modes (sliding friction, swing friction and rotating friction). Also, the effects of three movement modes on the friction lubrication of PVA/HA composite hydrogel are explored. PVA/HA composite hydrogel was bonded with the acetabulum of ultra-high-molecular-weight polyethylene (UHMWPE) by the chemical bonding method, and the friction and wear properties are tested by hip simulation experiments. The bearing and damage mechanism of PVA/HA composite hydrogel is studied, which provides theoretical basis for the study of bionic joint repair materials.

2. Experiment material and method

2.1. Preparation method of PVA/HA composite hydrogel

Potassium dichromate and concentrated sulfuric acid were weighed with mass percent of 1:4. It was put into the thermostat water bath with 70°C. It was stirred to uniformity and dichromate oxidation solution formed. The UHMWPE sample was immerged in the 70°C dichromate oxidation solution for 10 min. PVA, HA and deionized water were weighed with mass percent (15% PVA, 3% HA and 82% deionized water). After swelling 24 h under room temperature, it was immerged in the thermostat water bath with 95°C. The PVA/HA composite hydrogel solution was produced. PVA and deionized water were weighed with mass percent of 7% and 91.5%. The former steps were repeated and PVA solution was produced. Concentrated sulphuric acid with 1.5% were put into as catalyst and grafting solution was produced. The cleaned UHMWPE sample was immerged in the grafting solution and put into the thermostat water bath with 90°C for 2 h. The UHMWPE sample was cleaned with 90°C deionized water to clean the unreacted PVA. The produced 15%PVA and 3%HA composite hydrogel was put into the surface UHMWPE sample to make PVA/HA composite hydrogel reach to 2mm. The sample was put into the cooled storage incubator with −20°C for 6–10 h and thawed for 2–3 h under the room temperature. This process was repeated for 9 times and PVA/HA composite hydrogel artificial cartilage was produced [19].

2.2. Acetabulum grafting PVA/HA composite hydrogel

The UHMWPE was processed into acetabulum with roughing treatment to increase the reacting area for oxidative esterification and the fixed area with hydrogel. Its diameter is 32 mm. Stainless steel metal ball joint was processed to match the acetabulum, and its diameter is 28 mm. Using the methods of chemical grafting which is shown in the Section 2.1 to prepare acetabulum grafting PVA/HA composite hydrogel. It was put into the cooled storage incubator with −20°C for 6–10 h, and thawed at room temperature for 2–3 h. This process was repeated for 9 times and acetabulum grafting PVA/HA composite hydrogel was produced (Fig. 1).

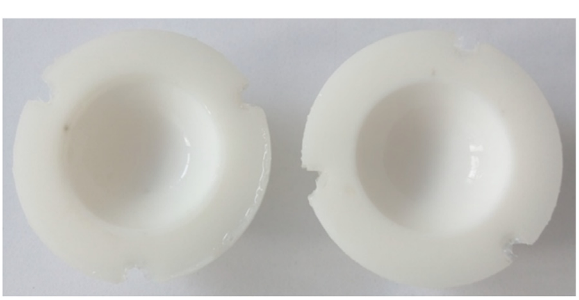

Fig. 1. UHMWPE acetabulum with PVA/HA composite hydrogel.

2.3. Experiment device and parameter

The sliding, swing, rotation friction tests was carried on the UMT multi-functional micro friction testing machine to test the cobalt chromium molybdenum (CoCrMo) alloy balls with PVA/HA composite hydrogel (Test diagram is shown in Fig. 2). The diameter of CoCrMo ball is 28 mm, and The UHMWPE sample of sliding friction is 20 mm × 20 mm × 30 mm. The thickness of the PVA/HA composite hydrogel is 2 mm, and lubricating media is 25% bovine serum. The sliding test loads are chosen as 10 N, 20 N, 30 N and 40 N and the speeds are chosen as 1 mm/s, 5 mm/s, 10 mm/s, 20 mm/s, 30 mm/s, 40 mm/s and 60 mm/s. The sliding distance of CoCrMo ball is 10 mm, and the experimental parameters are shown in Table 1.

The swing test load are 10 N, 20 N and 30 N and the swing angle are 5°, 10° and 15°, which is shown in Table 2. The rotation test load of are 10 N, 30 N and 50 N and the rotation angle are 5°, 10° and 15°, which is shown in Table 3. The UHMWPE sample of swing friction and rotation friction is φ30 mm.

2.4. Friction finite element model of PVA/HA composite hydrogel

2.4.1. Sliding friction finite element model of PVA/HA composite hydrogel

According to the size of PVA/HA composite hydrogel and CoCrMo alloy ball, the friction finite element model of CoCrMo alloy ball and PVA/HA composite hydrogel was established. The thickness of the PVA/HA composite hydrogel is 2 mm, and the thickness of UHMWPE is 2 mm. The diameter of CoCrMo alloy ball is 28 mm. Saint-Venant method is used to simplify this model. The CoCrMo ball was divided into 14608 entity unit with 8 node reducing integration (C3D8R), and PVA/HA composite hydrogel was divided into 22560 entity unit with 8 node pore pressure integration (C3D8RP). The UHMWPE was divided into 22560 entity unit with 8 node reducing integration (C3D8R), and the model of CoCrMo ball and PVA/HA composite hydrogel was established (Fig. 3). The face-to-face contact effect was used to simulation analysis, molybdenum cobalt chromium ball surface was set as the main plane and PVA/HA composite hydrogel as minor plane. PVA/HA composite hydrogel was fixed with UHMWPE to restrain the movement of UHMWPE on the direction of horizon, vertical and rotation. The pore pressure of PVA/HA composite hydrogel layer surrounding was set as 0 [20–25]. The sliding speed and load are shown in Table 1, and the material properties are shown in Table 4.

2.4.2. Swing and rotation finite element model of PVA/HA composite hydrogel

According to the size of PVA/HA composite hydrogel and CoCrMo alloy ball, the swing and rotation friction finite element model of CoCrMo alloy ball and PVA/HA composite hydrogel was established. The thickness of the PVA/HA composite hydrogel is 2 mm, and the thickness of UHMWPE is 2 mm. The diameter of CoCrMo alloy ball is 28 mm. Saint-Venant method is used to simplify this model. The CoCrMo ball was divided into 14608 entity unit with 8 node reducing integration (C3D8R), and PVA/HA composite hydrogel was divided into 22560 entity unit with 8 node pore pressure integration (C3D8RP). The UHMWPE was divided into 22560 entity unit with 8 node reducing integration (C3D8R), and the model of CoCrMo ball and PVA/HA composite hydrogel was established (Fig. 4). The material properties are shown in Table 4.

The face-to-face contact effect was used to simulation analysis of swing. The CoCrMo ball surface was set as the main plane and PVA/HA composite hydrogel as minor plane. PVA/HA composite hydrogel was fixed with UHMWPE to restrain the movement of