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The effect of synthetic polymer lubricants on the friction between common arthroplasty bearing biomaterials for encapsulated spinal implants

F.A. Alnaimat, D.E.T. Shepherd *, K.D. Dearn

Department of Mechanical Engineering, School of Engineering, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK

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ABSTRACT

There are two major problems with ball and socket artificial joints; the migration of wear particles inducing an inflammatory response, causing toxicity, osteolysis and subsequent implant loosening; and the poor tribology between interstitial or synovial fluid and device's articulation surfaces. Experiments have been conducted to assess the potential of the promising bio-lubricant polyvinyl alcohol (PVA) at different concentrations with a range of materials (combinations of CoCr, UHMWPE and PEEK). Tests were conducted on a pin-on-disc tribometer and results were compared against Ringer's solution and bovine calf serum. The highest friction coefficient was for CoCr/CoCr for all lubricants. The lowest, and superlubricity was measured for UHMWPE/CoCr (a friction coefficient of 0.009) with 20 g/100 ml PVA (PVA-C).

1. Introduction

Ball and socket articulations are widely used for joint replacement implants such as those for the spine and hip. A significant problem that can arise in joint replacement implants is the generation and subsequent migration of wear particles resulting from the combined rolling and sliding between the socket against the ball [1–3]. In this case, when the wear debris reaches the surrounding tissues it can cause problems such as inflammation, toxicity, osteolysis and then implant loosening [4,5]. The size and shape of generated debris are also likely to change throughout the life of an implant, further complicating these problems [6].

An improved lubrication regime can help to minimise the generation of these wear particles. It has been proposed that joint replacement implants might benefit from a capsule which can seal an artificial lubricant within the joint to reduce friction and wear, whilst simultaneously preventing debris from migrating [7,8]. This study is the first part to developing an encapsulated disc replacement (Fig. 1) where the friction of various biomaterials and lubricants was investigated. A commercially available example of this is the Bryan disc (Medtronic Sofamor Danek, Inc., Memphis, TN), which relies on the idea of using encapsulation with saline solution as a lubricant. The disc has shown promising clinical results [9–11]. It seems reasonable therefore that a biocompatible polymer based lubricant could be used with joint implant replacements. Synthetic polymer lubricants have been used since the 1960s [12]. More recently, Kobayashi et al. [13] have used polyethylene glycol (PEG) as a synthetic polymer lubricant with synovial fluid to lubricate knee replacements. In natural synovial joints, the lubricant is synovial fluid and the lubricity of this fluid is similar to water due to the high shear rates inside these prostheses [14]. In disc replacements, the implants are likely to be lubricated with interstitial fluid which has low viscosity and a value for lubricity between Ringer's solution and bovine calf serum, both of which are lower than synovial fluid [15,16]. This relatively low viscosity is likely to lead to challenging tribological conditions for any spinal implant device that relies on bearing surfaces. If encapsulation is to be successful in spinal implant devices, there will be a need to find an appropriate synthetic lubricant to reduce friction and wear, and increase implant durability.

Polyvinyl alcohol (PVA) has been shown to be a promising lubricant because of its physical properties, the lubricity of the solution and its biocompatibility [17,18]. PVA is one of the water soluble polymers which comes as solid white granules or as a powder. The solubility of PVA depends on the degree of hydrolysis in water [19]. PVAW40/140 with 5% and 10% was studied as a synthetic lubricant for synovial joints [18]. PVA and polyvinylpyrrolidone (PVP) have been used in artificial tear fluids with appropriate viscosity to lubricate dry eyes [20]. PVA hydrogels have been developed as an artificial membrane in contact lenses [21]. The material has also been used as a hydrogel membrane for

* Corresponding author. Tel.: +44 121 414 4266.
E-mail address: d.e.shepherd@bham.ac.uk (D.E.T. Shepherd).

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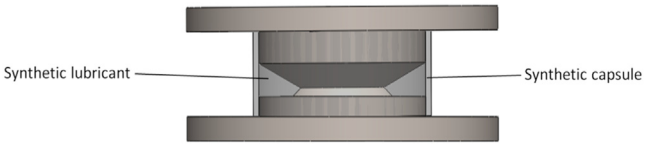

Fig. 1. Artificial disc prosthesis with synthetic capsule and lubricant.

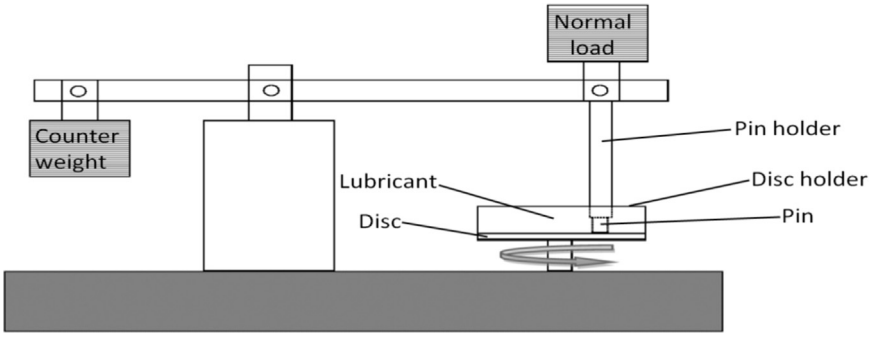

Fig. 2. A schematic representation of the pin on disc tribometer.

Table 1
Surface roughness of test specimens.

Material	Mean roughness ± Standard deviation (μm)
CoCr Disc	0.92 ± 0.05
CoCr Pin	1.11 ± 0.02
UHMWPE Pin	0.82 ± 0.11
PEEK Disc	0.87 ± 0.06
PEEK Pin	1.26 ± 0.04

the encapsulation of implanted Langerhans islets cells in the pancreas to immunoisolate them from the immune response [22,23]. It has also been used by Jiang et al. [24] as a one piece tricuspid heart valve made entirely from PVA hydrogel. PVA was also been used as an artificial articular cartilage to repair joint surfaces [25], as well as the film coatings for pharmaceutical and dietary supplement tablets where a barrier is required to protect tablets from moisture and other contaminants. PVA is not considered as carcinogenic and there are no reports related to the chronic toxicity and carcinogenicity when it is taken orally [26].

The aim of this study was to compare the frictional behaviour of the most widely used materials in artificial discs with potential synthetic lubricants for use in encapsulated implants. PVA of different viscosities, Ringer's solution and bovine calf serum were used as the test fluids. In addition, lubricant viscosity, modified by PVA concentration was also assessed.

2. Materials and methodology

2.1. Tribological specimens

The test samples comprised an upper pin and a lower disc. The upper pin samples were machined to 8 mm diameter and 15 mm length, the lower disc samples were machined to 79 mm diameter and were 5 mm in thickness. The tested materials were cobalt chrome (CoCr) alloy Haynes 25/L605 [27] supplied by (Dynamic Metals Ltd. Hemel Hempstead, UK), ultra high molecular weight polyethylene 1000 (UHMWPE), unreinforced polyether ether ketone (PEEK) 450G (supplied by Direct Plastics Ltd. Sheffield, UK). These materials have been previously tested for spinal implants [28,29].

All of the tribological specimens were polished using a Buehler Alpha Grinder Polisher (Buehler Ltd. Illinois, USA). The surface roughness of each pin and disc was measured three times using an Alicona G4 InfiniteFocus (Alicona, Raaba, Austria). The results of the surface roughness measurements are shown in Table 1.

2.2. Lubricants

Three types of lubricant were used in this study, although it should be noted that several concentrations of polyvinyl alcohol (PVA) were tested. They were:

- Ringer's solution – prepared with a 1.2 g Ringer's solution tablet (Oxoid Ltd., Hampshire, UK) in 500 mL of distilled water.
- Bovine calf serum – prepared by defrosting the serum (SeraLab, West Sussex, UK) over 24 h at 5 °C before diluting with 20 g/L deionized water and adding 0.3 g of sodium azide powder to minimize bacterial growth (Sigma-Aldrich, MO, USA).
- PVA – prepared from powder with a molecular weight of 31,000–50,000 g/mol, 98–99% hydrolysis. The PVA was prepared at 80 °C and the concentrations of PVA were:
  - PVA A: 4 g per 100 mL of distilled water.
  - PVA B: 10 g per 100 mL of distilled water.
  - PVA C: 20 g per 100 mL of distilled water.
  - PVA D: 30 g per 100 mL of distilled water.

2.3. Viscosity measurements

The viscosities of the different PVA lubricants were measured using an AR-G2 cone on plate rheometer (TA Instruments Ltd., West Sussex, UK). A 60 mm diameter standard steel cone with a 2° angle was used to measure the viscosity of the lubricants.

A lubricant volume of 8 ml was placed between the cone and the plate of the rheometer using a plastic pipette. The cone was then lowered until there was direct contact between the cone, plate and lubricant. The cone was positioned with a truncation gap of 54 μm [30].

The experiment was performed at 22 °C for shear rates from 0.1 s^{-1} to 1000 s^{-1}. Three tests were undertaken for each lubricant and the mean viscosity with 95% confidence intervals calculated.

2.4. Tribological experiment

Tribological tests were conducted using a bespoke pin on disc tribometer as used in previous studies for biomedical materials for