Acta Biomaterialia 7 (2011) 710–715

Contents lists available at ScienceDirect

Acta Biomaterialia

journal homepage: www.elsevier.com/locate/actabiomat

Wear analysis of unicondylar mobile bearing and fixed bearing knee systems: A knee simulator study

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ARTICLE INFO

Article history:
Received 26 July 2010
Received in revised form 22 September 2010
Accepted 24 September 2010
Available online 29 September 2010

Keywords:
Wear
Unicondylar knee
Mobile bearing
Fixed bearing
Polyethylene

ABSTRACT

Unicondylar knee arthroplasty is an attractive alternative to total knee arthroplasty for selected patients with osteoarthritis. Mobile bearing knee designs have been developed to improve knee kinematics, lower contact stresses and reduced wear of ultra-high molecular weight polyethylene compared with fixed bearing designs. This study compared in vitro wear behavior of fixed and mobile unicondylar bearing designs. Analysis was performed using a force-controlled AMTI knee simulator according to ISO 14243-1:2002(E). The wear volume of the implants was determined gravimetrically. Optical surface characterization and an estimation of wear particle size and morphology were performed. Implant kinematic data for both designs were determined. The wear rates averaged 10.7 ± 0.59 mg per 10^6 cycles for the medial and 5.38 ± 0.63 mg per 10^6 cycles for the lateral components of the mobile bearings, compared with 7.51 ± 0.29 mg per 10^6 cycles and 3.04 ± 0.35 mg per 10^6 cycles for the fixed bearings. The mobile bearings therefore exhibited higher wear rates ($P < 0.01$) compared with the fixed bearings. The tibial polyethylene inserts of the mobile bearings showed pronounced backside wear at the inferior surface. The kinematics of both designs was similar. However, anterior–posterior translation was lower in the mobile bearings. The wear particles were mainly elongated and small in size for both designs ($P = 0.462$). This study shows that wear may play an important role in unicondylar mobile bearing knee designs. Advantages of unicondylar mobile designs compared with fixed bearing designs, which have been proposed in terms of wear behavior and improved kinematics, could not be confirmed.

1. Introduction

Wear of ultra-high molecular weight polyethylene (PE) in artificial knee joints is a particularly important factor in the longevity of joint replacements [1–3]. Wear debris has been shown to lead to cellular reactions resulting in periprosthetic bone loss (osteolysis) and eventual loosening of implants [4–6]. Several factors affecting wear, such as patient weight, activity level, joint lubrication, motion patterns, implant manufacturing method and sterilization method have been studied [7]. Implant design is a critical factor influencing wear behavior. Hence, a wide range of different implant designs are available on the market with the aim of minimizing overall wear.

In addition to conventional total knee arthroplasty (TKA), unicondylar knee arthroplasty (UKA), replacing only one condyle of the knee joint, has been introduced. This concept is based on the assumption that a less invasive approach along with preservation of the knee ligaments should lead to a more physiological function of the knee joint [8]. Greater range of motion has been reported after UKA compared with TKA [9–11]. However, nearly all studies with follow-ups of 10 years or greater show that UKA will have inferior survivorship compared with TKA [12].

In fixed bearing designs the PE insert is rigidly coupled with the metal tibial tray, either by screws or a snap-fit mechanism; articulation occurs exclusively between the superior surface of the insert and the femoral component. Multidirectional forces are therefore applied to the insert via its superior surface. In the case of mobile bearings the insert has two articulating surfaces; articulation occurs between the femoral condyle and the superior surface of the insert and the inferior surface of the insert and the tibial tray. Decoupling of multidirectional motions in the mobile designs is generally expected to reduce cross-shear. Larger contact areas by two separate articulating surfaces and increased conformity will lower contact stresses at the PE insert in the mobile designs. It has been proposed that these aspects will reduce wear in mobile bearing compared with fixed bearing designs [13,14].

This study was designed to investigate the hypotheses that: (1) the unicondylar mobile bearing design wears less than the fixed

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doi:10.1016/j.actbio.2010.09.031

bearing design; (2) mobility in the mobile bearing design is increased compared with the fixed bearing design; (3) the amount, size and morphology of wear particles is different in the two designs. To answer these questions a wear study on mobile and fixed unicondylar knee designs was performed using a physiologically acting knee simulator.

2. Materials and methods

A moderately conforming fixed bearing (Univation® fixed, Aesculap AG, Tuttlingen, Germany) and a highly conforming mobile bearing knee design (Univation® mobile, Aescualp AG) were evaluated in the present study (Fig. 1). Medium sized components of both designs were manufactured in a similar manner: the femoral components were made of cast CoCr29Mo alloy according to ISO 5832–4, tibial trays were made of forged CoCr29Mo alloy according to ISO 5832–12, and tibial inserts were made of PE (GUR 1020) according to ISO 5834–2. The thickness of both β-irradiated (dose ~30 kGy) tibial inserts was 7 mm. The tibial inserts of the fixed bearing design were attached to the tibial tray by a snap-fit mechanism, whereas for the mobile bearing design internal–external (IE) rotation as well as anterior–posterior (AP) and medial–lateral (ML) translation of the insert were not restricted. Wear behavior of eight samples was analyzed in a simulation of the right knee. Clinically, most unilateral replacements are performed in the medial compartment [15]. Since the design is unicompartmental, two components were paired to simulate the medial and lateral compartments (Fig. 2). To simulate the lateral compartment of a right knee the medial components of a left knee were used, since lateral components are not in clinical use for this implant design. One pair of components was used as a soak control and was only loaded axially.

2.1. In vitro wear simulation, implant kinematics and surface characterization

Force-controlled simulation according to ISO 14243-1:2002(E) was carried out in an AMTI knee simulator (model KS2-6-1000, Advanced Mechanical Technology Inc., Watertown, MA) [16,17]. Compressive load, applied to the paired components, was offset medially 5.2 mm from the varus–valgus axis to create higher forces on the medial compartment [18,19]. Simulation was carried out in recirculated diluted calf serum (PAA Laboratories GmbH, Pasching, Austria) in a sealed chamber, maintained at 37 ± 1 °C. A protein concentration of 30 g l^{-1} was chosen according to Noordin et al. [20]. Sodium azide (NaN_3) and ethylenediamine tetraacetic acid (EDTA) were added to retard bacterial growth and minimize layers of calcium phosphate on the implant surfaces. Prior to simulation the tibial inserts were presoaked in serum and gravimetrically measured at weekly intervals. The tibial inserts were presoaked until the incremental mass change of the inserts was less than 10% of the cumulative mass change. The following test parameters were employed: a maximum load of 2600 N, a flexion angle of 0–58°, AP force of –265–110 N, and an IE rotational torque of –1–6 Nm. Motions were limited by a linear path-dependent, AP constraining force of 30 N mm^{-1} and a path-dependent, rotational constraining torque of 0.6 Nm per degree. Simulation lasted a total of 5×10^6 load cycles at a frequency of 1 ± 0.1 Hz. Every 0.5×10^6 cycles the components were cleaned and gravimetrically measured according to ISO 14243-2:2000(E). To minimize inter-station variability tibial inserts were rotated between wear stations every 0.5×10^6 cycles. Serum was replaced at the same intervals. Kinematic implant data (AP translation and IE rotation) were recorded during simulation to evaluate the mobility of the implant systems. Wear scars were documented photographically after 5×10^6 load cycles using the optical camera of a coordinate measuring machine (MS 222, Mahr GmbH, Göttingen, Germany).

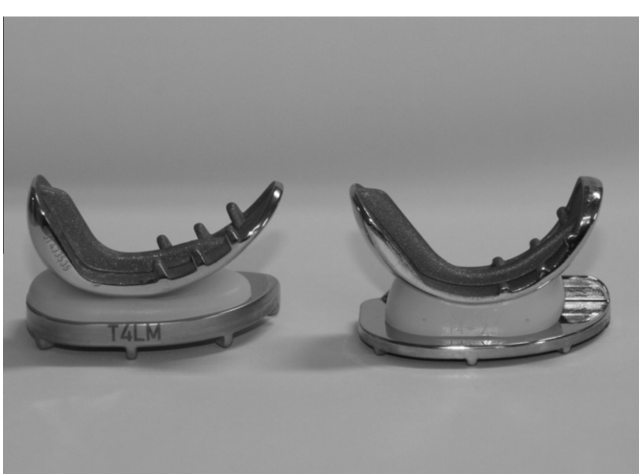

Fig. 1. Investigated implants: fixed (left) and mobile (right) unicondylar bearing designs.

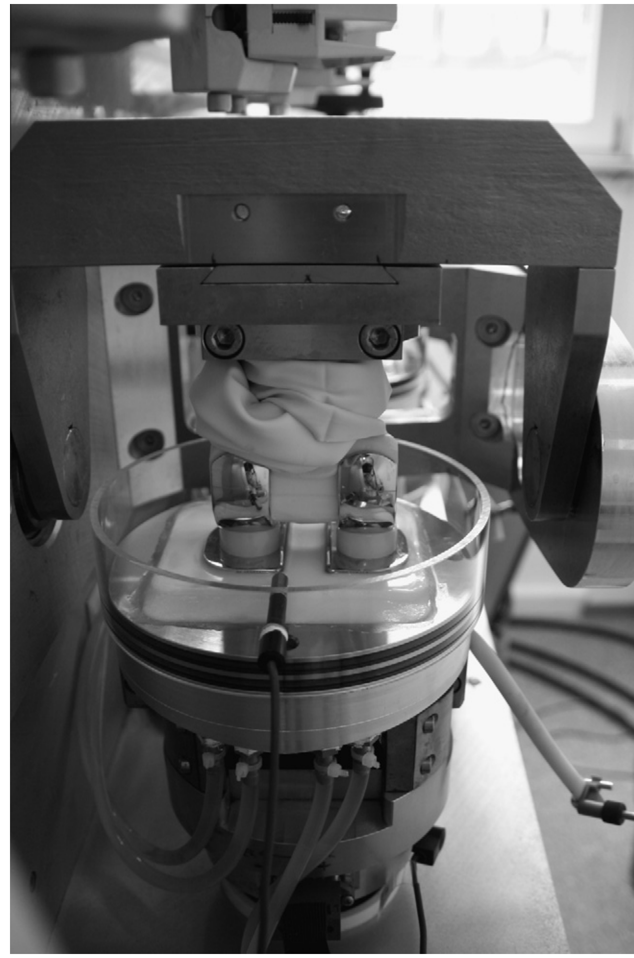

Fig. 2. Experimental set-up: AMTI knee simulator with implants mounted in wear stations. Two unicondylar components were paired to simulate the medial and lateral compartments.

2.2. Particle analysis

Wear particles were isolated from the serum lubricants collected after 4.5×10^6 cycles. The method of serum digestion was