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UHMWPE acetabular cup creep deformation during the run-in phase of THA's life cycle

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ABSTRACT

Ultra-high molecular polyethylene (UHMWPE) is one of the most used materials of the acetabular liners in total tip arthroplasty (THA). Polyethylene has good tribological properties and biocompatibility. However, the lifetime of polyethylene implants is limited by wear related complications. Polyethylene material released into the periprosthetic environment induces osteolysis that can be followed by implant loosening. Wear of cup is influenced mainly by orientation of the cup in pelvis, by initial geometry before the material degradation and by tribological parameters. Aim of this study is to focus on the run-in-phase of the liner which is predictive for future life cycles of liner. Creep deformations of liners for 30°, 45°, 60° inclination angles surgically recommended for the positioning in pelvis were analyzed by the optical scanning method. Load tests were performed for 50,000 cycles. Creep deformations and surface changes were analyzed at each 10,000 cycles. The results showed that liners with 60° inclination angle had higher creep deformations. Penetration of femoral head was 0.04–0.05 mm and occupied bearing area was around 77%. The smallest creep was measured for the 45° angle. However, deformation in the superior quadrant of acetabular rim, which is vulnerable for potential fracture of a liner, was identified in this case. Topography of the surface bearing was also observed during the run-in-phase. The surface was smoothened and showed multidirectional scratches caused by the influence of third body particles. This phase was followed by early delamination. Flakes sized approximately 5–20 µm were observed on the UHMWPE surface. This is similar to the'flake' shape wear debris extracted in vivo. Detailed analysis of run-in phase of loading of modern polyethylene implants can help to distinguish between their creep deformation and true degradation. The latter contributes strongly to the development of wear related complications associated with THAs limiting substantially their time in service.

1. Introduction

The main factor limiting longevity of metal on polyethylene (MoP) hip replacement is wear of the Ultra High Molecular Weight Polyethylene (UHMWPE) acetabular cup. Mutual motion of bearing surfaces of the THA, identified as multidirectional cross shear motion (Turell et al., 2003), causes deliberation of polyethylene particles from an articulating surface.

As it has been stated in multiple studies (Gallo et al., 2017; Gibon et al., 2017; Ingham and Fisher, 2000), deliberated polyethylene particles of critical sizes 0,3–10 µm (Green et al., 1998) can cause inflammatory biological reaction causing osteolysis of the bone that surrounds components of the THA. This can eventually lead to aseptic loosening of the THA requiring its imminent surgical revision.

Thus, there is a consistent effort to reduce wear rate of UHMWPE cups, to increase THA's lifespan and to minimize the need for a revision surgery. There has been a notable progress in material development in the form of second (XLPE) and third (Vitamin E doped XLPE) generations of UHMWPE that show better wear resistance. Besides the material development, there are numerous studies focusing on other factors affecting wear rates of THA in vivo, such as acetabular cup orientation in human body (Korduba et al., 2014; Scheerlinck, 2014).

Spatial orientation of acetabular cup in patient's body is determined by anteversion and inclination angles. There are surgically recommended intervals for both of these angles being 5–25° for anteversion and 30–50° for inclination (Bobman et al., 2016). Altering the inclination angle significantly affects the properties of the contact area. Increasing the inclination angle shifts the area of contact pressure closer towards the acetabular rim, while decreasing its overall size and increasing its maximal value of contact pressure (Hua et al., 2016).

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While influence of the acetabular orientation on the contact stress is well documented, a direct relationship between the contact pressure properties and wear mechanism is not yet fully understood. Older studies found no significant correlation between higher wear rates and higher inclination angles (Del Schutte et al., 1998; Patil et al., 2003). On the other hand, some more recent studies showed decreasing wear rates with increased inclination angles (Halma et al., 2014; Korduba et al., 2014; Rijavec et al., 2014). There are also generally higher wear rates when measured with radiography than obtained by simulator wear tests (Kang et al., 2003).

These rather significant differences between numerous studies could be caused by multiple factors. For example, simulator studies with strictly controlled conditions do not take into account loose third body particles of bone void fillers (Cowie et al., 2016) or bone cement. There are also different approaches to wear measurement. The radiographic method, used in clinical practice, displays head's penetration as result of wear and plastic deformation (creep) of polyethylene acetabular cup. This analysis is less accurate and determines only the linear wear (Ebramzadeh et al., 2003). It is also difficult to identify released polyethylene apart from creep plastic deformation of a liner using this method. In vitro volumetric measurements are on the other hand performed using various methods such as gravimetry, coordinate-measuring machine (Lord et al., 2011; Uddin, 2014) or optical methods (Choudhury et al., 2018; Ranuša et al., 2016; Zou et al., 2001). These methods are used on retrieved cups or during in vitro simulator wear tests. The key difference is that gravimetric methods show solely physical loss of liners material, caused by abrasion, adhesion and fatigue which are subsequent to hip articulation (Affatato et al., 2008), whereas analysis of liners surface (Ranuša et al., 2017) shows complex information about combined wear and creep processes. Gravimetry bears the problem of joint fluid soak which needs to be accounted for, surface analysis on the other hand presents the challenge of distinguishing material loss of the liner from its creep behavior.

Creep behavior of polyethylene acetabular cup has been observed in multiple computational studies, hip simulator studies and clinical studies on retrieved THAs. It has been stated in the computational studies (Bevill et al., 2005; Liu et al., 2012; Penmetsa et al., 2006), that major part of the creep deformation occurs in the very first phase of the acetabular wear, when bearing surfaces are adjusting to each other. The creep deformation changes spherical geometry of acetabular cup and alters contact area of the THA implants. While there is the Finite Element Method (FEM) analysis for the initial phase of wear, it involves certain simplifications regarding the creep model, loading and kinematic conditions and surface geometry. Moreover, there is lack of in vitro data on the initial wear. Hip simulator studies (Affatato et al., 2017; Galvin et al., 2010) are mainly focused on long term wear testing and first measurements of articulating surfaces are usually carried out far beyond the initial run-in phase of the THA. Creep in the run-in phase was observed in vivo on early retrieved THAs (Muratoglu et al., 2004). Authors concluded, that creep degradation was predominant in this phase. Surface texture changes caused by creep degradation affect tribological properties (friction, wear intensity) of the MoP bearing in pin on plate configuration (Niemczewska-Wójcik and Piekoszewski, 2017).

The aim of this study is therefore to observe creep degradation of polyethylene acetabular cups during the run-in phase. For the first time, measurements in this phase are based on in-vitro hip simulator testing. Changes of surface geometry validate the existing simplified FEM analysis (Bevill et al., 2005; Liu et al., 2012). Measurement of the creep deformation depth could improve the accuracy of head penetration measurements using radiography and thus narrow the gap between in vivo and in vitro wear rate measurements. The study also helps to clarify the impact of the plastic deformation of cups on the tribological characteristics of hip implants as well as the impact of the cup orientation on the wear rate. The surface texture of bearing surfaces is observed together with the friction coefficient to describe the run-in phase of the wear cycle more closely.

2. Materials and methods

The run-in phase was observed on Polyethylene-on-Metal hip replacement using acetabular cup components (B-Braun, Aesculap AG et Co. KG, Germany) paired with corresponding CrCoMo femoral heads from the same manufacturer. All of the cup liners were made from compression molded GUR 1020 UHMWPE – Chirulen, according to International Organization for Standardization (ISO-5834-2). The irradiation dose (applied in a N_2 environment) was between 25 and 37 kGy (Milošev et al., 2012). The inner surface radius of all cup liners was 14 mm. The outer shape of cups was also spherical with diameters varying between 58 mm and 60 mm, similar liner wall thickness was chosen because it was identified as factor influencing the creep deformations. The cup components were intended for cemented fixation. Brand new samples of these components, commonly used in clinical practice, were used in this study. Acetabular cups were placed in high strength resin (Dentacryl, SpofaDental a.s., Czech Republic) simulating placement in bone cement.

Three physiological orientations with different inclination angles were tested each with test sample number of n = 1. Inclinations of 30°; 45° and 60° were chosen to represent the whole surgically recommended inclination interval. Anteversion angle was the same in all three tested replacements to isolate the influence of inclination. The chosen anteversion was 15° approximately in the middle of the recommended interval.

The tested hip replacements were subjected to physiological loading and motions using the hip simulator. The simulator was fully servo-driven and featured uniaxial load and two motion axes. The physiological load was applied via spring compression using twin peak 3000 N load gait cycle with 1 Hz frequency according to the ISO 14242-1.

The orientation of the two motion axes relative to the load line was chosen to simulate Flexion-Extension (applied on the femoral head, range − 18°/+ 25°) and Inner-Outer rotation (applied on the acetabular cup, range − 10°/+ 2°) motions. Lack of the third motion (Abduction-Adduction) axis specified in ISO 14242-1 was compensated by a phase shift of F/E and I/O sinusoidal motion curves by 90° in comparison to ISO 14242-1 (Fig. 1).

The elliptical motion of the bearing surfaces, causing multidirectional shear stress typical for the physiological load (Turell et al., 2003) was maintained in this way. It has been also stated (Ali et al., 2016) that replacing Abduction-Adduction axis with phase shift of other two axes does not have notable impact on wear rates and deformations of an acetabular cup while simulating the gait cycle (Fig. 2).

The hip replacement components were submerged in model-synovial fluid during simulator testing. The fluid was based on PBS solution with addition of Albumin (28 mg/ml) and γ-globulin (9.4 mg/ml) proteins. During the testing, the whole containment with flooded hip

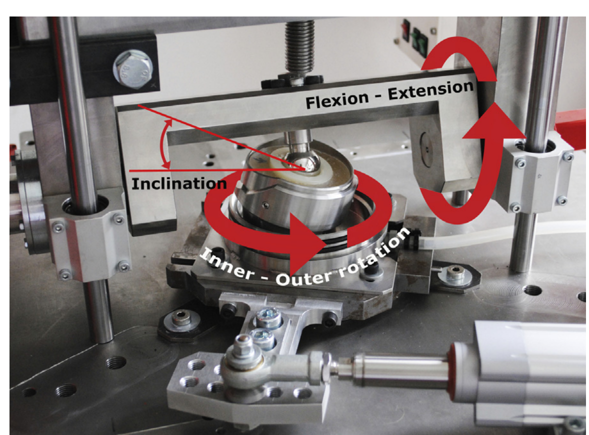

Fig. 1. The kinematic of hip joint simulator.