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Research Paper

Effect of size and dimensional tolerance of reverse total shoulder arthroplasty on wear: An in-silico study

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ABSTRACT

Although huge research efforts have been devoted to wear analysis of ultra-high molecular weight polyethylene (UHMWPE) in hip and knee implants, shoulder prostheses have been studied only marginally. Recently, the authors presented a numerical wear model of reverse total shoulder arthroplasties (RTSAs), and its application for estimating the wear coefficient k from experimental data according to different wear laws. In this study, such model and k expressions are exploited to investigate the sensitivity of UHMWPE wear to implant size and dimensional tolerance. A set of 10 different geometries was analysed, considering nominal diameters in the range 36–42 mm, available on the market, and a cup dimensional tolerance of $+0.2$, -0.0 mm (resulting in a diametrical clearance ranging between 0.04–0.24 mm), estimated from measurements on RTSAs. Since the most reliable wear law and wear coefficient k for UHMWPE are still controversial in the literature, both the Archard law (AR) and the wear law of UHMWPE (PE), as well as four different k expressions were considered, carrying out a total of 40 simulations.

Results showed that the wear volume increases with the implant size and decreases with the dimensional tolerance for both the wear laws. Interestingly, different trends were obtained for the maximum wear depth vs. clearance: the best performing implants should have a high conformity according to the AR law but low conformity for the PE law. However, according to both laws, wear is highly affected by both implant size and dimensional tolerance, although it is much more sensitive to the latter, with up to a twofold variation of wear predicted. Indeed, dimensional tolerance directly alters the clearance, and therefore the lubrication and contact pressure distribution in the implant. Rather surprisingly the role of dimensional tolerance has been completely disregarded in the literature, as well as in the standards. Furthermore, this study notes some important issues for future work, such as the validation of wear laws and predictive wear models and the sensitivity of k to implant geometry.

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1. Introduction

Reverse total shoulder arthroplasty (RSTA) is an accepted option to treat rotator cuff tears since its clinical outcomes are better than those of anatomical implants. Nevertheless, the literature reports a revision rate of RTSAs in the range 0–22% at the short-medium term follow up (33–52 months) (Nam et al., 2010b). There are multiple causes of failure associated with shoulder prostheses. Fevang et al. (2009) showed that aseptic loosening due to osteolysis was the main cause of revision of RTSA in Norway. Scapula notching is a recognized complication with RTSA. This may be linked with impingement but it has also been suggested that wear particles may contribute to it too (Nyffeler et al., 2004). This view has been restated recently as motivation for consideration of more wear resistant materials in shoulder arthroplasty (Peers et al., 2015). In addition, several types of wear damage, from pitting and edge deformation to abrasion and delamination, have been observed in retrieved components of RTSA (Nam et al., 2010a; Day et al., 2012; Dillon et al., 2015; Wiater et al., 2015). Therefore, wear is a recognized critical factor in shoulder arthroplasty.

Although huge research efforts have been devoted to wear analysis/predictions of UHMWPE-on-metal hip and knee prostheses (Mattei et al., 2011, 2013b; Mattei and Di Puccio, 2013a), shoulder implants have gained interest only recently and require further studies. The causes of wear of RTSAs have been investigated mainly experimentally. In particular, the effect of some design characteristics on implant wear has been investigated, among which: the presence of a hole at the dome of the bearing cup surface due to the fixation screw (Vaupel et al., 2012), retentive vs non retentive profiles of the glenoid surface (Carpenter et al., 2015), the irradiation grade of UHMWPE (Peers et al., 2015) and the inversion of the bearing materials (Kohut et al., 2012). With the exception of the irradiation grade of UHMWPE, all the above mentioned factors revealed only a slight influence on the implant wear rates. Among the few numerical studies on wear of RTSAs, (Ribeiro et al., 2011) and (Quental et al., 2015) analysed the effect of the clearance and the glenoid lateral offset, respectively, but unfortunately the reliability of their results is limited because of the use of wear coefficients originally estimated for hip and knee implants, which have been shown to be much lower (up to −58%) than the shoulder wear coefficients (Mattei et al., 2016).

Actually, the influence of the implant geometry on RTSA wear has never been deeply investigated in the literature, although it certainly plays a major role as it directly affects the contact and lubrication conditions in addition to muscle force, joint load and range of motion (Langohr et al., 2015). In particular, as for a ball-in-socket joint, the most important geometrical features of RTSA are the cup/head diameter (d_c and d_h, respectively) and the diametrical clearance ($cl = d_c - d_h$), as demonstrated for hip implants (Leslie et al., 2008; Tudor et al., 2013). Commercially available RTSAs are said to have high conformity, therefore, they are usually characterized only by their nominal diameter d_n mainly within range 36–42 mm. However, for practical purposes, a certain diametrical mismatch between the cup and head must be guaranteed in order to preserve the lubrication of the surfaces. The value of the mismatch depends on design criteria as well as on the manufacturing processes. Though, while the dimensional tolerances of implant components are fundamental both for implant clinical outcomes and for wear investigations, they are generally not described in standards (e.g. ASTM F1378) or in research studies. Moreover, also the effect of the real geometry of RTSAs, i.e. measured d_h and d_c, has never, to the authors' best knowledge, been discussed in the literature. The only study that reports some theoretical values of cl is (Ribeiro et al., 2011), which simulated 36 mm RTSAs with $cl = 0$, 0.02, 0.10 mm. It should be observed that $cl = 0$ mm represents an ideal conformity between surfaces, which is practically an unrealistic configuration.

The aim of the present study was to numerically investigate the influence of implant size and dimensional tolerances on wear of RTSAs. Wear predictions were carried out using an analytical and parametric wear model presented by the authors in (Mattei et al., 2016) and based on experimental wear investigations (Smith et al., 2015; Mattei et al., 2016). A set of 10 simulation geometries was considered, including different implant sizes, with d_n varying from 36 to 42 mm, and a cup dimensional tolerance in the range $+0.2$, -0.0 mm (resulting in cl ranging between 0.04 and 0.24 mm). On the other hand, the dimensional tolerance of the metallic head was considered negligible, as explained in §2.2.1. The values of dimensional tolerances were derived from measurements on five samples of RTSAs mentioned in (Smith et al., 2015; Mattei et al., 2016). Since the most reliable wear law/wear coefficient for metal-UHMWPE bearings is still controversial in the literature (Mattei et al., 2013b), each simulation case was carried out assuming both the Archard wear law and a wear law for UHMWPE proposed in (Liu et al., 2011), and four different expressions of the wear coefficient, specific for RTSAs (Mattei et al., 2016). Consequently, this study proposes a combined sensitivity analysis (for a total of 40 simulations) of

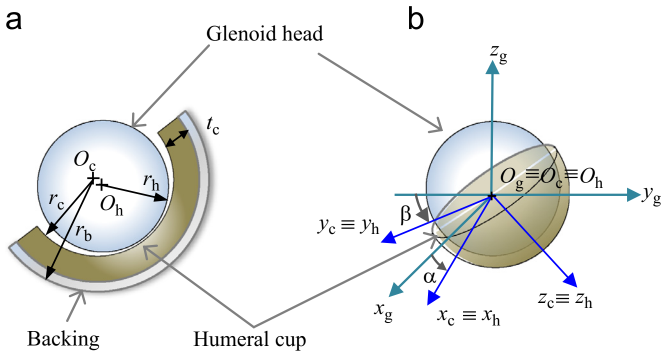

Fig. 1 – Model geometry (a) and coordinate frames in the reference configuration with no loading and null rotations (b). Note that r stands for radius, thus $r_h = d_h/2$ and $r_c = d_c/2$; r_b is the outer radius of the backing while t_c is the cup thickness.