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Research Paper

Numerical and experimental investigations for the evaluation of the wear coefficient of reverse total shoulder prostheses

Lorenza Mattei[a,*], *Francesca Di Puccio*[a], *Thomas J. Joyce*[b], *Enrico Ciulli*[a]

[a]*Department of Civil and Industrial Engineering, Largo Lucio Lazzarino 2, Pisa 56126, Italy*
[b]*School of Mechanical and Systems Engineering, Stephenson Building, Claremont Road, Newcastle upon Tyne, NE 1 7RU UK*

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ABSTRACT

In the present study, numerical and experimental wear investigations on reverse total shoulder arthroplasties (RTSAs) were combined in order to estimate specific wear coefficients, currently not available in the literature. A wear model previously developed by the authors for metal-on-plastic hip implants was adapted to RTSAs and applied in a double direction: firstly, to evaluate specific wear coefficients for RTSAs from experimental results and secondly, to predict wear distribution. In both cases, the Archard wear law (AR) and the wear law of UHMWPE (PE) were considered, assuming four different k functions. The results indicated that both the wear laws predict higher wear coefficients for RTSA with respect to hip implants, particularly the AR law, with k values higher than twofold the hip ones. Such differences can significantly affect predictive wear model results for RTSA, when non-specific wear coefficients are used. Moreover, the wear maps simulated with the two laws are markedly different, although providing the same wear volume. A higher wear depth (+51%) is obtained with the AR law, located at the dome of the cup, while with the PE law the most worn region is close to the edge. Taking advantage of the linear trend of experimental volume losses, the wear coefficients obtained with the AR law should be valid despite having neglected the geometry update in the model.

1. Introduction

Reverse total shoulder arthroplasty (RTSA) is considered the gold standard to treat rotator cuff tear arthropathy (Fig. 1a). It is also used to revise failed anatomical total shoulder arthroplasties (ATSAs) and to treat proximal humeral tumors and fractures. RTSA is performed by replacing the humeral head and the glenoid cavity with a plastic cup in ultra high molecular weight polyethylene (UHMWPE) and a metallic head respectively (Fig. 1b), in a geometrical reversed configuration with respect to the anatomical one. First introduced in the 1970s, RTSA has become popular only recently, thanks

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[*] *Corresponding author*. Tel.: +39 3492506500.
E-mail address: l.mattei@ing.unipi.it (L. Mattei).

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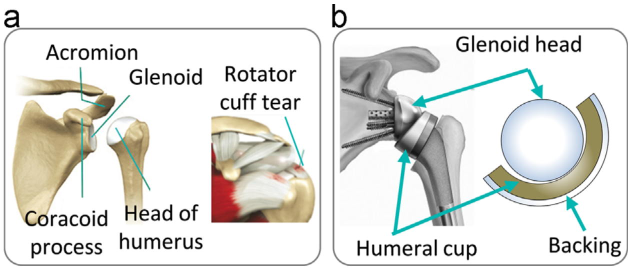

Fig. 1 – Shoulder anatomy and rotator cuff tear (a). Reverse shoulder implant and model geometry (b).

to the modern Grammont design (Boileau et al., 2005) and its FDA approval in 2003. The Grammont design is characterized by a large glenoid head, without neck, and a humeral cup with an almost vertical axis that allows, respectively, (i) a medialization of the center of rotation, which helps to minimize the torque at the glenoid component–bone interface and to recruit more deltoid fibers, (ii) a lowered position of the humerus with respect to the acromion, which restores and increases the deltoid tension. As a consequence, the modern reverse design results in (iii) a wider range of motion (up to 90° of abduction) and a more stable implant.

Although clinical outcomes are encouraging, the rate of complications and revisions is high, probably because the reverse design significantly alters the biomechanics of the natural shoulder joint. According to the literature, the most common complication is the inferior–posterior scapular notching, with an incidence of 0–100%, whilst the main cause of revision is glenoid loosening with an incidence up to 10% (Boileau et al., 2005; Farshad and Gerber, 2010; Nam et al., 2010; Wiater et al., 2014). It is widely recognized that notching is seen in explanted reverse shoulder implants (Nam et al., 2010; Nyffeler et al., 2004; Kohut et al., 2012) and that such notching can be a cause of substantial amounts of polyethylene wear debris. Further, this mechanical impingement puts the fixation at greater risk due to removal of supporting bone under the glenoid component. However it has been suggested that scapular notching may be made worse by wear debris from the articulating surfaces (Vaupel et al., 2012). It is also recognized that notching may be reduced by modifications to implant designs (Chou et al., 2009; Kohut et al., 2012) and optimal positioning of components. Therefore it is important to understand and determine the wear due to 'normal' articulation in reverse shoulder prostheses so that a baseline can be established (Smith et al., 2015).

In comparison to hip and knee implants, wear in shoulder prostheses has not been thoroughly investigated. Indeed, no wear test standards exist and there are very few shoulder simulators. Likely this is due to the extreme complexity of the shoulder joint and to the wide variety of daily shoulder movements. Consequently, only a few experimental investigations on wear of RTSA can be found in the literature (Kohut et al., 2012; Peers et al., 2015; Smith et al., 2013), which simulate different (and hardly comparable) working conditions. For instance, loading and motion profiles tested in (Kohut et al., 2012) are adapted from ISO 14242 for hip implants, whilst (Peers et al., 2015; Vaupel et al., 2012) simulate alternating cycles of flexion and abduction.

Numerical wear investigations on RTSA are restricted to a few studies (Quental et al., 2015; Ribeiro et al., 2011; Terrier et al., 2009), which are mainly focused on the comparison between anatomical and reverse solutions and often simplified in terms of simulated conditions (e.g. unloaded abduction–adduction) and wear law (e.g. Archard law with a constant wear coefficient) (Ribeiro et al., 2011; Terrier et al., 2009). Indeed, only in (Quental et al., 2015) the fundamental cross-shearing effect of the UHMWPE wear is considered assuming the new formulation of the wear law for UHMWPE recently proposed by Liu et al. (2011). Actually, the main limit of all such wear models lies in the values/expressions assumed for the wear coefficient k, since they were originally estimated for hip (Maxian et al., 1997; Saikko, 2006) and knee (Abdelgaied et al., 2011) implants. In fact, as is well known, the wear coefficient does not depend only on the material coupling but is also notably affected by the implant geometry, the loading/kinematic conditions and the lubrication regime. Consequently, k should be considered as a very specific quantity, which can be estimated by means of experimental and numerical wear simulations reproducing the effective working conditions (Di Puccio and Mattei, 2015a). Therefore, the use in wear modeling of RTSA of a value for k derived for hip/knee implants can compromise the reliability of wear simulations. On the other hand, to the best of authors' knowledge, wear coefficients of RTSA components are not available in the literature.

The main purpose of the present study is to evaluate reliable wear coefficients for RTSAs by means of numerical and experimental investigations, which are useful to characterize and compare RTSA designs, and as input data for numerical wear simulations. An experimental wear test on 42 mm diameter RTSA samples was carried out using a recently developed multi-station shoulder wear simulator (Smith et al., 2013). The test was then numerically simulated using an analytical wear model presented in (Mattei et al., 2013) and here adapted to shoulder implants. In particular, two wear laws were simulated. These were the Archard law and one for the wear of UHMWPE. In each case different expressions of the wear factor k were considered, also including the cross-shear effect. The comparison of experimental and numerical wear volumes allowed several wear coefficients which is innovative with respect to the literature.

2. Materials and methods

2.1. Experimental wear investigation

A 2 million cycle wear test was performed with JRI Orthopaedics Reverse VAIOS shoulder prostheses (Smith et al., 2013) using a recently developed multi-station shoulder wear simulator, presented in (Smith et al., 2015). The test group consisted in five shoulder prostheses each with a 42.1 mm diameter UHMWPE cup and an average diametrical clearance of 0.14 mm. Fig. 2 shows some of these components with the metallic glenosphere shown on the far right of the image and the UHMWPE humeral component on its immediate left. Also indicated is where the UHMWPE component fits inside its test bath. An additional sixth prosthesis was subjected to