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Lubrication and wear modelling of artificial hip joints: A review

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ABSTRACT

The tribological performance of artificial hip joints is a critical issue for their success, because adverse tissue reaction to wear debris causes loosening and failure. Many studies on wear and lubrication of hip prostheses have been published in the last 10 years, mostly on experimental tests. Theoretical/numerical models have been proposed for investigating geometrical and material parameters also. This paper reviews recent literature on lubrication and wear models, stressing simplifying hypotheses, input data, methods and results. It is pointed out that actually lubrication and wear are described neglecting each other while new advanced models including both aspects could be helpful.

1. Introduction

The hip joint is a spherical joint between the femoral head and the acetabulum in the pelvis (Fig. 1); it is a diarthrosis or synovial joint, since it is wrapped in a capsule that contains the synovial fluid (SF), a biological lubricant that acts also like a shock-absorber [1]. Thanks to the presence of the SF and to the *ball-in-socket* geometry, the hip joint can transmit high dynamic loads (7–8 times the body weight) and accommodate a wide range of movements.

Despite its remarkable characteristics, the hip joint can be affected, more often in aged people, by chronic pain and diseases such as osteoarthritis, rheumatoid arthritis, bone tumors or traumas. In these cases, the best clinical solution is the total hip arthroplasty, a surgical procedure that replaces the unhealthy hip joint with an implant, preserving the synovial capsule. Nowadays about 200,000 and 80,000 interventions/year are performed in the USA and in the UK, respectively, and they are estimated to increase of about 170% by 2030 [2]. Although hip arthroplasty is considered one of the greatest achievements in orthopaedic surgery in the last decades, from an engineering point-of-view hip implants are not a complete success and still need further developments. In particular they tend to have a limited service life of about 15 years, which is not satisfactory for patients under 60 years of age, about the 44%, demanding a life expectancy in excess of 20 or 25 years [3,4]. For these patients, an alternative and less invasive resurfacing technique has recently gained new interest [5]; in this approach the bearing couple of the total replacement implant is maintained, although with relatively larger dimensions, as shown in Fig. 2.

To date two main critical issues for implant success are agreed: the implant fixation/loosening related to the implant/bone interaction and the wear of the articulating surfaces (femoral head and cup surfaces). The adverse tissue reactions to wear debris causes loosening and implants failure [6], therefore the importance of biotribology in the development of long term artificial hip joints comes rather straightforward.

The lively research in this field is proven by the huge number of studies published in the last years: nearly 300 papers since 2000, most of them, about 200, on experimental tests for wear assessment. Theoretical models of wear in hip implants have been developed only recently and are typically oversimplified with respect to the real case; for instance the wear caused by adhesion and abrasion is simulated as a whole, without distinguishing the separate contributions. On the other hand, investigations on implants lubrication have mainly a theoretical approach, since only few groups can do tests on such elements [7]. Indeed experimental and theoretical researches complete each other in the effort of increasing service life of hip implants, that means mainly promoting fluid-film lubrication and minimizing wear. In fact on one side theoretical/semi-empirical models help to transfer laboratory test results to *in-vivo* conditions, and on the other side they can be used to predict long-term behaviour, which would require expensive and time-consuming tests.

The present paper reports a review of the state of the art of both lubrication and wear models, focusing on their main characteristics and recent developments. At our best knowledge

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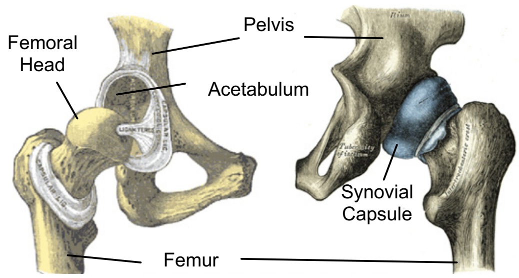

Fig. 1. Anatomy of the hip joint—left: "dissected" joint, right: synovial capsule (adapted from Gray's Anatomy Tables).

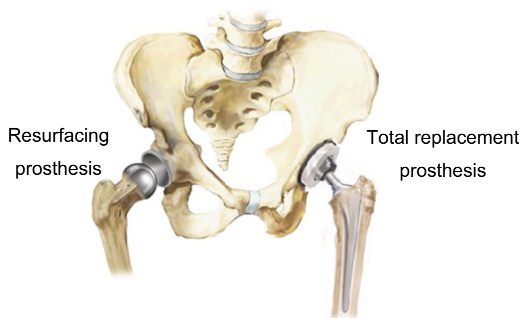

Fig. 2. Total replacement and resurfacing hip prostheses.

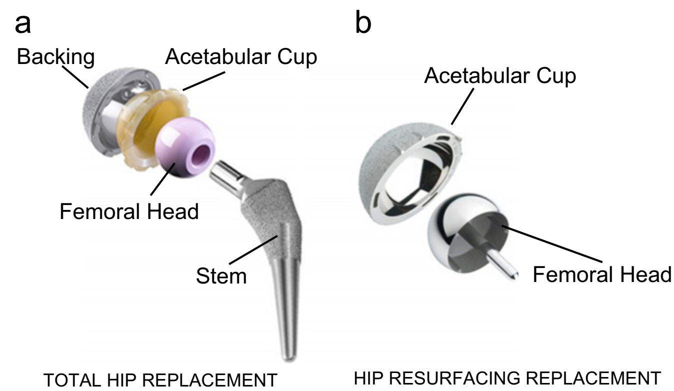

Fig. 3. Main components of an artificial hip joint.

Table 1
Mechanical properties of materials and typical roughness values for hip implant cup and head: Young's modulus E, Poisson's ratio ν, average roughness R_a.

Material		E (GPa)	ν	R_a (μm)
P	UHMWPE	1	0.4	0.1 – 2.5
M	Stainless steel	210	0.3	0.01 – 0.05
	CoCrMo	230		
C	Alumina	380	0.3	≈ 0.001
	Zirconia	210		

the latest reviews on lubrication models have been proposed in 2006 [8,9] and include also experimental aspects of wear, while specific studies on wear mechanisms and hip wear simulators are reported in other recent surveys [10,11]. Nevertheless a review of wear modelling, cannot be found in the literature. Consequently this study aims to provide the reader an original, critical and complete analysis of the most important theoretical aspects of hip implant tribology.

2. Artificial hip joint

The main elements of the hip prosthesis are shown in Fig. 3. In the total hip replacement (THR) there are a femoral stem, sunk into the medullary canal of the femur, a femoral neck, connecting the stem to the head and an acetabular cup that is embedded in the pelvis, in some cases through a backing insert (Fig. 3a). In resurfacing hip replacement (HRR) only the bearing couple, i.e. the acetabular cup and the femoral head, remains (Fig. 3b).

All materials employed are biocompatible. In THR the femoral stem and neck are generally in stainless steel, cobalt-based alloy or titanium-based alloy, while the backing can be made from metal or plastics depending on its function. The metallic one is used with a plastic cup, in order to guarantee its fixation to the pelvic bone, whereas the plastic backing is used with metal or ceramic cup, for absorbing dynamic loads.

The most common choice for the bearing surfaces, classified on the basis of material type, i.e. plastic (P), metal (M) and ceramic (C), are the following [12]:

- head: M: stainless steel, CoCr and CoCrMo alloy; C: alumina and zirconia;
- cup: P: UHMWPE, M: CoCr and CoCrMo alloy, C: alumina.

The mechanical properties (elastic modulus E and Poisson's ratio ν) of the above mentioned materials and typical roughness values R_a are reported in Table 1. In addition, only in few cases titanium based alloys (e.g. Ti_6Al_4V) are used as material for the acetabular cup or the femoral head [12,13].

The crucial issue for the bearing surfaces is the head–cup material couple, which is strictly related to wear; almost since the beginnings, around the 1960s, the most used combination is *metal-on-plastic* (MoP), with a cobalt–chromium alloy head paired with a plastic cup. MoP and *ceramic-on-plastic* (CoP), also denoted as *soft on hard* couples, are known to suffer from wear of the plastic part whose debris generate an adverse tissue reaction. In order to reduce the wear rate, alternative *hard-on-hard* material combinations have been prompted, both as *metal-on-metal* (MoM), used also for HRR, and *ceramic-on-ceramic* (CoC). However also these combinations have drawbacks: in MoM implants the main problem is related to the presence of potentially cancerous metal ions, developed from wear particles; on the other side the ceramics are brittle, therefore require particular care during intervention, and have also some manufacturing downsides that made them the most expensive solution.

Although lubrication and wear models, described in the following sections, refer to head–cup material couple reported in Table 1, other solutions have been proposed to reduce hip implant wear. Among these, two promising solutions are worth mentioning in this survey: a wear resistant highly cross-linked polyethylene (HXLPE) and engineered surfaces by coatings.

In the 1990s in the attempt to improve the wear resistance of UHMWPE, new HXLPE liners were developed [14]. The first generation of HXLPEs, in clinical use, exhibited markedly less wear than conventional UHMWPE [15]; however, there have been some reports of surface cracking, mechanical failure and oxidative damage in failed acetabular liners [16,17]. In fact the cross-link formation, achieved by irradiation and melting of polyethylene, causes an alteration of the crystalline structure and, as a consequence, a reduction of mechanical properties. Replacing the melting with the annealing process allows to maintain the mechanical properties of polyethylene, but on the other hand the elimination of free radicals results poorly effective [18]. In order to overcome this drawback, a new process of sequential