Estimation of wear factors of MoM hip implants from simulator tests

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1. Introduction

Nowadays wear is recognized as one of the main concern of metal-on-metal (typically CoCr or CoCrMo alloy) hip implants (Figure 1), causing osteolysis and the release of dangerous metallic ions.

Figure 1 Worn MoM hip implants

Numerical wear simulations of hip implants are an attractive tool to investigate and predict long-term wear at low cost. A few wear models have been proposed in the literature for metal-on-metal (MoM) bearings [1-3], all based on the Archard wear law, as the adhesion and the abrasion are considered the main wear mechanisms. However, very recently, a few tribochemical studies have pointed out that the material loss is in part caused by the corrosion [4] and it should be taken in account in future studies. The reliability of the wear models mainly depends on a dimensional wear factor k whose evaluation/choice is actually a critical issue. Indeed k depends on many factors, such as lubrication regime, bearing materials and geometry, loading and kinematic conditions and thus can vary during a wear test as well as during the implant lifetime. To be reliable the wear factor should therefore be estimated in tests reproducing the effective working conditions, meaning that pin-on-disc results could be not suitable for the artificial joint wear assessment.

This complex scenario is simplified in wear simulations: firstly, two constant values of k, one higher for the initial running-in phase (k_{ri}) and the other lower for the steady state phase (k_{ss}), are typically assumed according to experimental observations (Figure 2). Secondly, in hip replacements, the same values of k_{ri} and k_{ss} are commonly attributed to the head and the cup. Such k values are generally estimated by matching numerical and experimental (total) wear volumes obtained by hip joint simulator tests [2, 3]. However, different wear maps can be obtained from numerical and experimental simulations, where material variability as well as test conditions can induce further discrepancies. Moreover, in a few studies, k is calculated even simulating conditions different from the experimental ones [2]. It is worth observing also that each research group has developed its own numerical (typically Finite Element Method, FEM) model, which can be another differentiating element in k estimation. All these reasons can explain the wide range of wear factors found in literature for hip implants, which span from 10^{-9} to 10^{-7} $mm^3/(N\,m)$. Thus, the reliability of k as well as of the wear models can be disputable.

The main aims of this study consist in: (i) estimation of wear factors of MoM implants from hip simulator tests, using a numerical wear model; (ii) highlighting correlations between k and implant characteristics/test conditions. Hopefully, as future developments, the results of this research will enable to provide more reliable values of k to be used in numerical simulations.

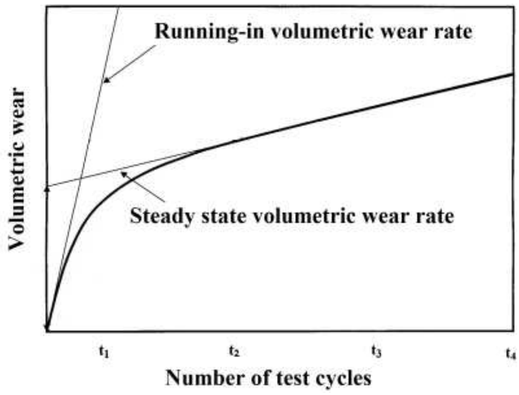

Figure 2 Volumetric wear trend for MoM hip implants

2. Experimental wear analysis

2.1. Hip wear simulators

Experimental wear analyses on hip implants are typically carried out using hip wear simulators. Such devices try to replicate the loading and kinematic conditions to which the hip implants undergo during their working-life, in order to achieve an estimation of the *in-vivo* wear rate. In most cases, as walking is assumed as the most common daily activity and thus the reference implant working condition, simplified gait cycles (frequency of 1 Hz) are simulated, up to 15 Mc.

The state of the art of the hip simulator includes many types of simulators [5], both academic and commercial, which can differ in load type, kinematics, cup position (i.e. anatomical A, or inverted NA) and orientation (i.e. inclination and anteversion), lubricant type (i.e. distilled water, bovine serum or synthetic ones). Specifically, the load can be applied to the head or the cup, can be fix or not to a component, and can have a fix or moving direction. The load profile, according to *in vivo* measurements [6], is generally characterized by a double peak, during the stance phase, followed by a constant value, during the swing phase (Figure 3-a). The minimum (L_{min}) and the maximum (L_{max}) load can vary in the range 100-3000 N. On the other side the kinematics try to reproduce the hip spherical motion characterized by the sequence of flexion-extension (FE), abduction-adduction (AA) and internal-external (IE) rotations. The simulator kinematics can include all or only some of the motion components. In both cases the angles and the rotations sequence must be specified. The motion can be assigned to a single component or both to head and cup (e.g. FE(h)+ IE(c) (Figure 3-b)). The variability of the tested conditions can be regarded as one of the cause of the high dispersion of wear volumes. This is even more evident for metal-on-plastic (MoP) implants, due to the cross-shear effect [4].

Wear tests in hip simulators can provide many useful information on the wear process, such wear volumes (e.g. by means of gravimetric measurements of implant or head/cup mass loss using accurate analytical balances) and linear wear maps of head and cup surfaces (e.g. using co-ordinate measuring machine). Unfortunately, in most studies only the total volumetric wear is reported and, to the best of our knowledge, no quantitative wear maps can be found in the literature.

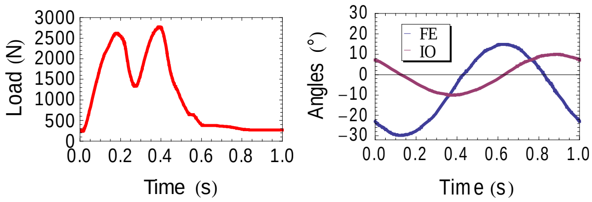

Figure 3 Typical loading and kinematic conditions of the Prosim simulator

2.2. Wear factor computation

The wear factor is a fundamental tribological quantity which relates the volumetric wear to the loading and kinematic conditions. Consequently k allows both to compare the wear generated by different wear simulators and to correlate the *in vivo* and the *in vitro* wear rates. Traditionally in pin-on-disk tests, the wear factor k is estimated from experimental data, according to Archard wear law, as

$$k = V^{\exp} \Big/ \int_{\gamma} F_N(s)\, ds \tag{1}$$

where $V^{\exp}$ is the experimental wear volume, F_N is the applied normal contact force and ds the relative sliding distance of the application point of the force. Consequently F_N is integrated over the force track γ, i.e. the track drawn on the counterface over a motion cycle by force application point (contact point). Equation (1) represents a simple expression suitable to pin-on-disk wear tests, where the contact force is generally constant along the force track and the contact pressure can be assumed to be uniformly distributed over the contact area. Unfortunately this is no longer valid for hip wear tests, where typically the force is time-dependent and the contact pressure is not uniform. That led to an improved formulation of k, proposed in [7]

$$k = V^{\exp} \Big/ \int_{\gamma} \int_{\bar{A}} \bar{p}(P,s)\, dA\, ds \tag{2}$$

where $\bar{p}$ is a simplified expression of the local instantaneous contact pressure and $\bar{A}$ the approximated contact area . Indeed, in [7], Equation (2) was applied to a MoP implant assuming sinusoidal/parabolic/ellipsoidal distributions of the contact pressure on the contact area, the latter approximated to the whole cup surface. Although Equation (2) introduces some improvements with respect to Equation (1), it still has some limitations: it approximates both the contact pressure and area (in location and size) and thus cannot be applied to MoM implants whose contact areas are much smaller than the cup hemisphere and moves over the cup/head surface.

A different approach for k computation is often adopted when a FEM wear model is available: k is estimated using a trial-and-error procedure by matching the predicted numerical wear volume with the experimental one. In such a case the real-like contact pressure/area are considered and a more reliable k estimation is obtained. On the other hand, an advanced FEM model is required, which can have a high computational cost. This numerical approach is adopted in the two wear MoM models available in the literature [2, 3].

All the methods described for k computation have in common some limitations: being based on the total wear volume of the implant, they cannot differentiate the cup and the head wear behaviour, i.e. cup/head wear factors, and completely neglect the real wear depth maps, which could be used as a model validation indicator.

3. Materials and methods

3.1. Analytical wear model

The analytical wear model used in the present study was presented by the same authors in [1]. The model is based on some simplifying hypotheses: the abrasion and the adhesion are the main wear mechanisms; the geometrical variation does not affect the contact mechanics; the contact is frictionless as the friction is demonstrated to not affect significantly the wear volumes. The model was implemented in Mathematica and was based on the Archard wear law. The latter was conveniently written in the local instantaneous form giving the linear wear of a point P on the worn surface in a cycle

$$h(P) = k \int_0^T p(P,t) \left| v(P,t) \right| \, dt \tag{3}$$

where $p(P,t)$ is the local instantaneous contact pressure, $\mathbf{v}(P,t)$ the local sliding velocity between head and cup, T is the cycle period (1 s). By integrating the Equation (3) over the worn area A, the total volumetric wear is obtained

$$V = k \int_A \int_0^T p(P,t) \left| \mathbf{v}(P,t) \right| \, dt\, dA \tag{4}$$

It is worth noting that the Equations (3,4) are applied separately for the head and the cup giving h_h and V_h, and h_c and V_c, respectively. When the wear factor is unknown, the wear volumes and depths scaled by k can be calculated as $\tilde{h}(P) = h(P)/k$, $\tilde{V}(P) = V(P)/k$.

This model allows rapid k evaluations thanks to the analytic parametric wear modelling (a simulation case takes less than a few minutes), and hence avoids the high computational costs typical of k evaluation by means of FEM models. Additionally, the powerful symbolic computation of Mathematica, can improve some discretization limitations of FE models.

3.2. Wear factor estimation

In this study an improved method for the computation of the wear factor is presented. The wear factor is estimated as the ratio of the experimental wear volume V^{exp} and the numerical wear volume scaled by the wear factor $\tilde{V}^{num}$, according to

$$k = V^{exp} \Big/ \int_A \int_0^T p(P,t)\,|\mathbf{v}(P,t)|\; dt\, dA \qquad (5)$$

With respect to methods of k computation available in the literature, the present one has several improvements: it is suitable to all contact types, not only to pin-on-disk as the traditional definition (Equation (1)); it is based on the real contact pressure and contact area, and thus can be applied to all hip implants typologies, differently from Saikko's method (Equation (2)). A further fundamental advantage deals with the possibility of differentiating the head and cup wear behaviour by estimating two different wear factors k_h and k_c.

Given the experimental wear volumes of the total implant $\tilde{V}_h^{num}$, the head $\tilde{V}_h^{num}$ and the cup $\tilde{V}_h^{num}$, the present model allows to calculated their correspondent wear factors k_{tot}, k_h, k_c, as follows

$$k_{tot} = V_{tot}^{exp} / \tilde{V}_{tot}^{num} \qquad (6)$$

$$k_h = V_h^{exp} / \tilde{V}_h^{num}, \quad k_c = V_c^{exp} / \tilde{V}_c^{num} \qquad (7)$$

In addition, using the estimated wear factors and Equation (3), it is possible to numerically evaluate the wear maps and the maximum wear depth both of head, h_{h_max}, and cup, h_{h_max}.

As the wear model does not implement the geometry update, only the running-in wear phase was considered and all data and results refer to it (i.e. $k = k_{ri}$).

3.3. Simulated cases

A literature review of the experimental wear studies on MoM implants was carried out and large a set of hip simulator tested conditions with the correspondent wear results was collected. It is worth noting that many of these studies do not provide all the data necessary for their simulation (e.g. load/angle curve not specified). In this paper only a subset of the simulated cases are described: two studies on total hip replacements (THRs) [8, 9] and three studies on hip resurfacing replacements (HRRs) [3, 10, 11], for a total of 10 simulated cases reported in Table 1. These studies were selected since carried out using the same hip simulator, the Prosim. As far as the kinematics is concerned, FE and IE are assigned to the head and the cup, respectively, whose angle curves are depicted in (Figure 3-b). The load is applied and fix to the head and thus continuously changes direction (load vertical for null FE angle). A Paul load type (Figure 3-a) is simulated, with a profile and L_{min} and L_{max} dependent on the test case. The loading conditions in [9] are an exception as simulate only the stance phase (still in 1s).

The analytical wear model presented in [1] was exploited to estimate wear factors of MoM hip implants, starting from experimental wear volumes available in the literature. Several simulations were carried out and a set of wear factors was calculated for different implant geometries (i.e. diameter and clearance), and loading conditions.

4. Results

The main results are reported in Table 2 (h_{max} values were calculated using k_h and k_c when available). An general overview of k_{tot} highlights a wide dispersion of such values, both for THRs and HRRs, ranging in 0.33–4.7 10^{-8} mm^3/(N m) and 1.25–3.95 10^{-8} mm^3/(N m), respectively. Such dispersion reflects the high sensitivity of the wear factor to the tested conditions.

Table 1 Simulated cases: geometry (head diameter d_h, diametrical clearance cl), load range ($L_{min} - L_{max}$) and volumetric wear rates for the running-in phase

ID	THR/ HRR	d_h (mm)	cl (μm)	Load (kN)	V_h (mm^3/ Mc)	V_c (mm^3/ Mc)	V_{tot} (mm^3/ Mc)	Ref.
1	THR	28	62.5	0.3 – 3	na	na	2.25	[9]
2		36	143		na	na	1.76	
3		36	124		na	na	1.41	
4		36	105		na	na	1.16	
5		28	60	0.1– 2	0.05	0.08	0.13	[8]
6		28	60	0.28 – 2	1.57	0.46	2.03	
7	HRR	38.5	111	0.2 – 3	na	na	2.58	[10]
8		54.5	126		na	na	1.15	
9		54.5	100	0.28 – 2.8	na	na	1.2	[3]
10		49.8	236	0.3 – 3	0.78	0.34	1.13	[11]

Table 2 Main results: estimations of the wear factors and the maximum wear depths of the running-in phase

ID	THR/ HRR	k_{tot} (10^{-8} mm^3/(N m))	k_h (10^{-8} mm^3/(N m))	k_c (10^{-8} mm^3/(N m))	h_{h_max} (μm)	h_{c_max} (μm)
1	THR	3.46	na	na	29.40	17.04
2		2.14	na	na	28.99	12.04
3		1.70	na	na	20.91	9.02
4		1.43	na	na	15.79	7.10
5		0.33	0.41	0.26	2.46	0.87
6		4.70	7.30	2.12	49.93	8.11
7	HRR	3.95	na	na	28.69	13.58
8		1.25	na	na	8.16	3.46
9		1.30	na	na	7.23	3.31
10		1.34	1.78	0.84	18.00	3.30

Firstly, the effect of the geometry on the wear is discussed, which is a debated issue. From a theoretical point of view, by analysing Equation (3,4), the larger the head, the larger the sliding distance and the contact area, and the lower the contact pressure. Consequently, it is difficult to a priori state which among these effects prevail and whether the wear increases or decreases with the head diameter [1]. The comparison between 28 mm vs 36 mm implants (case 1 vs cases 2-4) showed significantly higher wear rates for the smaller implant, which had k_{tot} and h_{max} higher up to 140%. On the other hand, the comparison of 38.5 mm and 54.5 mm implants (case 7 vs case 8) demonstrated an opposite trend: k_{tot} and h_{max} of the smaller implant were respectively 68% and 73% lower than the bigger one. Such a behaviour can be partially explained considering the lubrication regimes of the implants. As reported in [9], from 28 mm to 36 mm implants, a change of lubrication regime from boundary to mixed/fluid-film occurs, explaining the wear trend. The opposite trend observed in HRRs is hard to explain, but might be related to the different implant geometry and hence contact mechanics. Moreover, it should also be considered that the load applied in [9] differs significantly from the one in [8], since the former simulates only the stance phase. However, on the basis of the experimental data examined, it cannot be established who, among THRs and HRRs, has the better wear performance. The effect of the clearance (*cl*) is clearly showed by the comparison of cases 1-3, which tested 36 mm implants. The decrease of the clearance, which means an increase of contact conformity and a better lubrication, caused a decrease of k_{tot} and h_{max} of about 33% and 43%, respectively. The effect of the load on the wear factor was also investigated, resulting considerable. In [8] two identical implants were tested under similar wear profiles having the same L_{max} but different L_{min}: the swing phase load was 100 N and 280 N for the cases 5 and 6, respectively. The higher L_{min} of case 6 caused an increase of k_{tot} of about one order of magnitude.

An innovative aspect of this study concerns the evaluation of distinct wear factors for the head and the cup. Such estimation was carried out for the cases 5, 6 and 10. The results showed a significant difference between k_h and k_c: for instance, in case 6, k_h was even more than three-fold k_c. This can be explained by considering that the load was applied to the head. Such a difference is reflected on the wear depths: e.g., in case 6, h_{h_max} and h_{c_max} were 49.9 μm and 8.1 μm, respectively. The assumption of a similar wear behaviour of the head and the cup and the calculation of h_{h_max} and h_{c_max} using k_{tot}, would introduce errors on the wear depths up to 55% (e.g. 49.9 μm vs 32.1μm for h_{h_max}; 8.1 μm vs 18 μm h_{c_max}). The results showed that the wear redistribution among the head and cup, dependent on the working conditions, cannot be disregarded and is fundamental for predicting reliable wear maps.

5. Conclusions

In conclusion the wear factor is affected by many factors and must be evaluated separately for each bearing component. A reliable estimation of *k* requires to calculate it by simulating the exact experimental conditions. That suggests that pin-on-disc results, can hardly be used for artificial joint wear assessment. This particularly holds for MoP implants whose wear factor is strongly affected by the complex phenomenon of UHMWPE cross-shear [12]. Evidently, also reliable experimental wear volumes are crucial for reliable *k* evaluation. A discrete repeatability of the experimental tests is proved by similar wear factors of cases 8 and 9, which reproduced similar test conditions. On the other hand, unfortunately, many literature studies report high variations on V^{exp} measurements, up to 85% (e.g. [10]).

Future studies are aimed at evaluating mathematical correlations between *k* and the variables that affect it. Moreover the method will be applied to MoP implants, using the model presented in [12].

6. References

[1] Mattei, L., et al., "Wear simulation of metal-on-metal hip replacements with frictional contact", J Tribol, 135, 021402, 2013, 1-11.

[2] Harun, M.N., et al., "Long-term contact-coupled wear prediction for metal-on-metal total hip joint replacement", Proceedings of the Institution of Mechanical Engineers; Part J; Journal of Engineering Tribiology, 223, 7, 2009, 993-1001.

[3] Liu, F., et al., "Development of computational wear simulation of metal-on-metal hip resurfacing replacements", J Biomech, 41, 3, 2008, 686-694.

[4] Hesketh, J., et al., "Biotribocorrosion: Some electrochemical observations from an instrumented hip joint simulator", Tribol Int, 59, 0, 2013, 332-338.

[5] Affatato, S., et al., "Tribology and total hip joint replacement: current concepts in mechanical simulation", Med Eng Phys, 30, 10, 2008, 1305-1317.

[6] Paul, J.P., "Forces transmitted by joints in the human body", Proc Inst Mech Eng Part J J Eng Tribol, 181, 37, 1966, 8-15.

[7] Saikko, V., et al., "An improved method of computing the wear factor for total hip prostheses involving the variation of relative motion and contact pressure with location on the bearing surface", J Biomech, 36, 12, 2003, 1819-1827.

[8] Williams, S., et al., "Effect of swing phase load on metal-on-metal hip lubrication, friction and wear", J Biomech, 39, 12, 2006, 2274-2281.

[9] Dowson, D., et al., "A hip joint simulator study of the performance of metal-on-metal joints: Part II: Design", J Arthroplasty, 19, 8, Supplement, 2004, 124-130.

[10] Leslie, I., et al., "Effect of bearing size on the long-term wear, wear debris, and ion levels of large diameter metal-on-metal hip replacements - An in vitro study", Journal of Biomedical Materials Research Part B, Applied Biomaterials, 87 (Pt B), 1, 2008, 163-172.

[11] Li, C.X., "A hip simulator study of metal-on-metal hip joint device using acetabular cups with different fixation surface conditions", Proc Inst Mech Eng H J Eng Med, 225, 9, 2011, 877-887.

[12] Mattei, L., et al., "A comparative study on wear laws for soft-on-hard hip implants using a mathematical wear model", Tribol Int, 63, 2013, 66-77.