Third-body damage of prosthetic heads in total hip replacement: combined experimental and computational study

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Introduction
In artificial hip joints, the roughening of the femoral head has been associated to higher wear rates of the polymeric cup, eventually leading to osteolysis and implant failure. The increase of the femoral head roughness is strongly influenced by the presence of abrasive particulate entrapped between the articulating surfaces (Bauer et al., 1994 and Raimondi et al., 2000). This damaging mechanism has been simulated in controlled in vitro wear experiments (Que et al. 1999). The mechanical parameters influencing the scratch formation are still to be determined. The aim of the present study is to evaluate the dependence of such damage on the geometry of the hard particles entrapped in the joint, with reference to the commonly implanted UHMWPE/chrome-cobalt coupling. To this purpose, a series of chrome-cobalt femoral heads, retrieved at revision surgery after a period of in situ functioning, has been investigated for the occurrence of third-body damage. The damage observed on the surfaces has been divided into four typologies, on the basis of the defect morphology. A FE model has been built, which simulates the local behaviour of the two coupled bearing surfaces, in the presence of those entrapped hard particles. An index of induced head damage has been defined on the basis of the computational results and discussed in relation to the experimental findings.

Materials and methods
Experimental characterisation of the third-body damage.
Five sets of prosthetic heads plus the relevant acetabular liners have been studied. All were modular chrome-cobalt femoral heads coupled to the UHMWPE liners on which the prosthetic heads articulated in vivo. All the components were harvested at revision surgery 16 to 62 months after THA. Topology of the articular surfaces of each femoral head and acetabular cup has been examined using scanning electron microscopy (SEM). The third-body damage observed on the surfaces has been divided into four typologies on the basis of the defect morphology. Quantitative assessment of the surface topography has been achieved on each femoral head using contacting profilometry. The mean roughness, \( Ra \), has been calculated from ten \( Ra \) values obtained at different head locations.

Computational model of the third-body interaction.
The system studied is sketched in Figure 1. The model is composed of two solid cylinders, of radius 500 \( \mu \)m, and of an axisymmetric rigid surface contacting the cylinders. Element size ranges from 0.5 \( \mu \)m to 10 \( \mu \)m.
The chrome-cobalt alloy has been modelled as an isotropic elastic-perfectly plastic material, with Young’s modulus 206 GPa, Poisson’s ratio 0.3 and yield stress 830 MPa. UHMWPE has been modelled as an isotropic elastic-plastic material, with elastic limit 15 MPa and with work hardening up to a maximum yield stress of 52 MPa. A frictionless unilateral contact has been assumed between all interacting surfaces. The particle has been modelled as an infinitely rigid body. Two geometries have been assumed. The first is a sphere contacting both the UHMWPE and chrome-cobalt solids, of diameter 5, 10, 15, 20, 30 and 40 µm. The second geometry is an irregular prism, contacting the polymeric surface with the largest face and contacting the chrome-cobalt surface with a free sharp edge (Figure 4). The side in contact with the polymeric surface has been modelled as a disk of diameters 5, 10, 15, 20, 30 and 40 µm. The side in contact with the chrome-cobalt surface has been modelled as a 45° inclined wedge with a flat circular tip of diameters 2.5, 5, 7.5 and 10 µm.

The behaviour of the UHMWPE/particle/chrome-cobalt system has been simulated using two subsequent steps. Firstly, vertical displacement of the UHMWPE solid has been prescribed, until a maximum reaction force on the particle is reached. Secondly, the calculated force has been applied as a concentrated load on the particle in order to indent the chrome-cobalt solid.

After load removal, the mesh of the metal component is irreversibly deformed, as a result of residual plastic strains occurring beneath the indentation site. The peak to valley height of the deformed profile, $R_{y, FE}$, was calculated and assumed as an index of induced damage.

**Results and Discussion.**

SEM images representing each typology of damage found on the femoral heads are shown in Figure 2. Type I: short scratches showing a dashed track, consistent with the rolling of a sharp-edged hard particle. Type II: irregular scratches with a cross-section varying in shape, width and depth (arrows), consistent with an entrapped hard particle, sliding and rolling. Type III consists of scratches showing two parallel tracks (arrows), consistent with a sharp-edged particle, entrapped in the polymer and facing the chrome-cobalt surface with its corners. Type IV is a particle impression. All the heads with implantation time shorter that 24 months show a mean roughness value below 0.03 µm, typical of nonimplanted chrome-cobalt heads. Nevertheless, significant local damage has been found on all the components. The FE calculated peak to valley height of the indentation left by a spherical particle on the chrome-cobalt surface is plotted in Figure 3 against the sphere diameter.
The numerical simulations show how the geometric features of the scratch are related to the morphology of the hard particle (Figure 4). Such shape and size determine the maximum reaction force developed by the deformed polymer, which will act on the particle indenting the chrome-cobalt surface. In the case of a sphere, we found that an impression with peak to valley depth larger than 0.1 μm can be induced only by particles with a diameter larger than 10 μm. Detached porous coating beads may produce significant surface scratches while release of smaller oxides may not produce visible scratches. In the case of particles with an irregular shape, we found that the damage induced on the chrome-cobalt surface depends on a further factor, that is on the width of the particle’s free corner indenting the chrome-cobalt.

References.