Shape versus Size Relationship of Prosthetic Ultra-high Molecular Weight Polyethylene Wear Particles

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Atomic force microscopy (AFM) is used to characterize in detail ultra-high molecular weight polyethylene (UHMWPE) wear debris from a low contact stress (LCS) knee prosthesis, actuated with a state of the art knee simulator. The size and shape of debris particles is quantified in all three spatial dimensions. The three-dimensional AFM information indicates that for the prosthesis and the conditions studied here debris particles are mostly oblate, with the smallest particles having the greatest degree of deformation.

1. Introduction

Ultra high molecular weight polyethylene (UHMWPE) is the selected material for tibial inserts in total knee arthroplasty due to its low wear rate, excellent abrasion resistance and high mechanical stability [1, 2]. In spite of the adequate material properties, wear is observed because of the highly dynamic stresses experienced in a knee joint, therefore affecting the clinical performance of the joint. Particle debris created from the tibial insert interacts with many kinds of white blood cells and immune cells, starting a cascade of events that ends with prosthesis loosening and therefore revision surgery [3, 4].

The abundance and morphology of UHMWPE debris particles influences their bio-response. Irregularly-shaped particles have been shown to have an increased biological reactivity [5, 6, 7] compared with regular-shape debris. Our previous study [8] has demonstrated that for the prosthesis studied here but using a constant load actuator, micro-scale particles tend to be more spherical, whereas nanoscale particles have a tendency to be deformed with oblate, flake-like shapes.

Fractionation of different debris particle sizes has often been achieved by filtration, and images of the debris on the filter are typically obtained by scanning electron microscopy (SEM) [5, 6, 9]. With this technique, the two dimensional projection of a particle is determined, and some qualitative contrast information about the particle height can be inferred. With atomic force microscopy (AFM), in contrast, the size and geometry of polyethylene wear particles can be measured in all three spatial dimensions with a precision on the nanometre scale. AFM imaging has rarely been applied to characterize UHMWPE debris [10, 11, 12]. However, Scott *et al.* [11] have demonstrated consistency with scanning electron microscopy (SEM).

In order to expand our previous study [8], debris particles were created under realistic conditions using a PROSIM knee simulator. The size and shape of particles has been measured directly in three spatial dimensions with AFM.

2. Materials and methods

2.1. PROSIM knee simulator

A pristine knee prosthesis was actuated with a PROSIM single-station knee simulator (Simulation Solutions Ltd) in order to obtain UHMWPE wear debris particles. The prosthesis was a standard size, cobalt-chrome on UHMWPE, low contact stress (LCS) mobile bearing knee system (DePuy/Johnson & Johnson); see Fig.1 (a). A walking regime was simulated by following ISO standards (see Fig. 1 (b) and (c) for typical flexion-extension and axial load parameters). The simulation was performed for 3.7 days, which roughly equates to 6 months of walking. Since the focus of this work is on the spectrum of debris particles and their characterization, deionised water (Millipore Milli-Q) was used rather than bovine serum. Moreover, with water as lubricant the extraction is simplified.

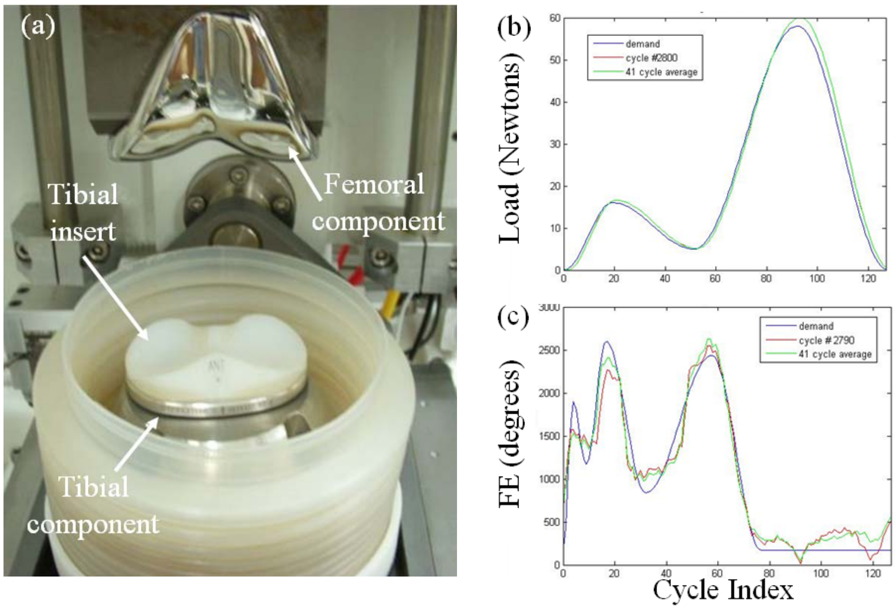

Fig. 1. (a) Photo of the LCS Knee prosthesis used in this experiment. (b) Flexion-Extension and (c) Axial load corresponding to a walking simulation (ISO standards).

2.2. Sample preparation

The water lubricant containing UHMWPE debris particles was collected at the end of the PROSIM simulation. Twelve particle size fractions were obtained following a novel filtration protocol [8]. The nominal filter pore diameters were 10, 5, 3, 1, 0.8, 0.6, 0.4, 0.3, 0.2, 0.1, 0.05 and 0.025 µm. Following filtration, each filter with debris particles was left to dry over 24 hours, stored on a covered Petri dish. In preparation for AFM characterization, a 10×10 mm^2 piece was cut out of the centre of the filter and attached with double-sided adhesive tape onto a mirror-finished silicon substrate. SEM images of wear debris particles on the 20-10 µm and 3-5 µm fraction filter medium are shown in Fig. 2 (a), (b). It is apparent that the particles tend to rest on their largest surface.

2.3. Atomic force microscopy

For each fraction, 5-10 images of debris particles on filter were taken with an AFM, NT-NTEGRA PRIMA (manufactured by NT-MDT) using semi-contact mode. The AFM tip scans a small area on the flat substrate and directly probes the height variations due to debris particles resting on the substrate. Height measurements with this technique have a precision in the nm-range. The lateral *x*- and *y*-resolution of the instrument is better than 20 nm, and the height resolution (*z*-coordinate) is better than 5 nm. In addition to images of filters with debris particles, several images of pristine filters were recorded for comparison. The instrument software package allows for automated particle size measurements. However, it was found that an artificial digitization of the data can occur. Therefore, the length, width and height of each particle in an image have been measured individually by using the length and the cross-sectioning tools of the software.

3. Results

In this work the length, width and height of a particle have been defined as previously published [8]. These three parameters were measured for all particles on the AFM images. Most of the particles tended to be non-spherical, with most of them having three significantly different measurements for length, width and height.

Figure 2 (c), (d) shows two typical images for the 0.6-0.8 µm and 0.2-0.3 µm fraction respectively. It is apparent that some of the particles are greatly elongated and fibril-like. Particles less elongated (almost spherical) are also present.

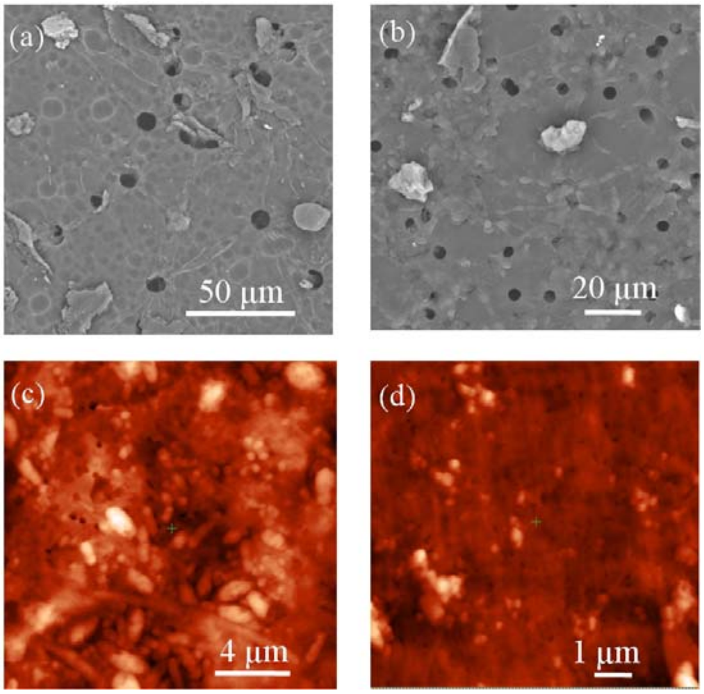

Fig. 2. SEM (top) and AFM (bottom) images of UHMWPE debris on filter paper. The filtered particle fractions shown here are: (a) 10-20 µm, (b) 3-5µm, (c) 0.6-0.8 µm and (d) 0.2-0.3 µm.

Our previous work [8] established that the sphericity *S* of a particle [13, 14] is an appropriate quantity to describe their shape. *S* is a measure of how spherical an object is, and it is defined as the ratio of the surface area of a sphere (with the same volume as the given object) to the surface area of the object. Values of *S* close to unity correspond to spherical shapes, whereas small values represent deformed particles. The volume of the particle was calculated assuming their shape can be approximated by an ellipsoid, the formula used was:

$$V = (4\pi/3) \times [(L/2) \times (W/2) \times (H/2)]$$

where *L*, *W*, *H* refer to the length, width and height respectively. The sphericity *S* for UHMWPE debris particles are displayed in Fig. 3 as a function of the ellipsoidal volume. Figure 3 (a) corresponds constant load actuator results [8], (b) to PROSIM knee simulator data.

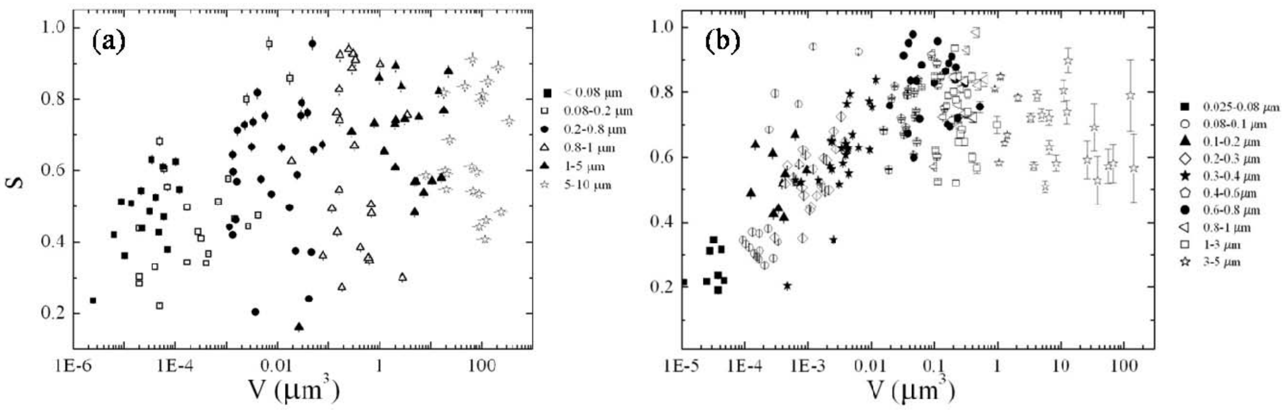

Fig. 3. Scatter plot of sphericity *S* as a function of particle volume for a walking simulation with a (a) constant load actuator [8] and (b) PROSIM knee simulator. It is apparent that particle sphericity increases with particle size.

In this representation, which takes into account measurements of all three spatial dimensions, an interesting relationship between shape and size is observed. It can be seen for both situations that small particles are strongly deformed, whereas larger particles tend to be less deformed with values of sphericity close to 0.7. On the filter paper, particles tend to precipitate by resting on a large area of their surface. Since the height tends to be significantly smaller than both length and width, which tend to be similar, most particles have oblate shapes. It was observed that the oblate nature of the particles persist for all filtration fractions.

The possibility that small debris particles may be deformed, as they are in this wear study, may have a bearing on their bioactivity.

4. Conclusions

UHMWPE wear debris was produced by actuating a knee prosthesis with a state of the art knee simulator. Atomic force microscopy has been found to be well suited for measurements of all three spatial dimensions of wear particles. For the knee prosthesis and the wear conditions studied here debris particles are mostly oblate, flake-like particles, with the smallest particles having the greatest degree of deformation. Accurate shape information may contribute to a better understanding of the wear mechanisms in prostheses and the bioactivity of UHMWPE particles.

Acknowledgments

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