X-ray computed tomography for wear measurement of prosthetic components

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Keywords: X-ray Computed Tomography, Joint prosthesis, Wear testing, Dimensional metrology, Volume measurements

Abstract

This work investigates capabilities and accuracy of metrological X-ray Computed Tomography (CT) in quantifying wear volumes and characterizing the geometry of prosthetic joint components. Advantages and limitations are determined in comparison with measurements by Coordinate Measuring Machines (CMMs). The work demonstrates that CT is advantageous especially for measuring polymeric prosthetic components.

1. Introduction

Wear volume measurement and geometrical characterization of bearing surfaces of prosthetic joint components are fundamental for understanding wear mechanisms and improving technological solutions provided by manufacturers of orthopaedic prostheses. Wear testing of prostheses is typically performed using wear testing machines that physically reproduces controlled loading and relative motion for millions of cycles on the bearing surfaces to be evaluated.

The current standard method for evaluating wear volumes of prosthetic components is the gravimetric method, using microbalances [1]. However, this method can quantify only globally the worn material, while it cannot provide local information on the worn surface geometry. In addition, it can be applied only for in-vitro testing of new prosthetic components and not for assessing retrieved parts (which may contain residuals). Furthermore, it cannot access other damages not involving material loss, such as plastic deformations. CMMs with tactile probes have recently been used as an alternative to the gravimetric method, overcoming most of its limitations [2].

However, the uncertainty of wear volume measurements from CMM data is in some cases too high, especially when polymeric components are measured, due to several drawbacks, including: probing force, fixation method, points sampling and alignment procedures. Industrial CT and CMMs are compared below.

2. Experimental

A number of samples were tested and measured using different measuring systems.

2.1 Samples

Both hip and knee prosthesis were studied. Concerning hip prosthesis, two types of bearings were examined: ceramic-on-ceramic hip prosthesis (where both the femoral head and the acetabular component are of ceramic material), and ultra-high molecular weight polyethylene (UHMWPE) cups. Concerning knee prosthesis, two types of polyethylene unicondylar knee prostheses (UKP) were examined: UHMWPE tibial inserts with congruous design and UHMWPE tibial inserts with non-congruous design. In addition to new components, also retrieved components were measured, which were removed from patients after years of implantation.

2.2 Measuring systems

CT measurements were performed at University of Padua using a metrological CT system: Nikon Metrology MCT225, with 225 kV liquid cooled micro-focus reflection source and air-cooled cabinet. The maximum permissible error (MPE) for length measurements, stated by the manufacturer based on tests in accordance to guideline VDI/VDE 2630 part 13, is MPE = $9 + L/50$ µm (where L is the length in mm).

The specimens were measured also by CMMs, for comparison with CT measurements and for dimensional calibrations, in addition to gravimetric calibrations from a microbalance. Two CMMs were used: (i) ZEISS Prismo VAST 7 equipped with tactile scanning probe head and (ii) Werth Video-Check IP 400 multisensor CMM equipped with touch-trigger probe, video imaging probe and laser distance sensor based on the Foucault principle (knife edge). In this work, the first CMM was preferred for performing tactile measurements, because of its scanning head that allows faster probing (which is advantageous for ensuring sufficiently close-meshed distribution of measured points [2]). The second CMM was used for optical measurements.

3. Results

Figure 1 shows an example of a wear map obtained from CT measurement of an UHMWPE acetabular cup with spherical bearing surface having nominal diameter equal to 30 mm. The expanded uncertainty (k=2) of volume measurement obtained in this case was below 30 mm^3, which correspond to 0.15% of the sample volume. Uncertainty was determined using the method proposed in [4].

Feldkamp effects [3] may affect considerably the results from CT measurements; for this reason, the sample orientation during CT scanning was chosen carefully, so that Feldkamp effects do not appear on the relevant zones for wear determination (as shown for instance in Figure 2). Errors introduced by the Feldkam effect are already taken into account in the volume measurement uncertainty.

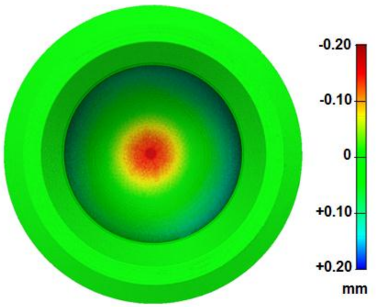

Figure 1: Deviation map showing wear distribution on the spherical bearing surface of an UHMWPE acetabular cup measured by CT system.

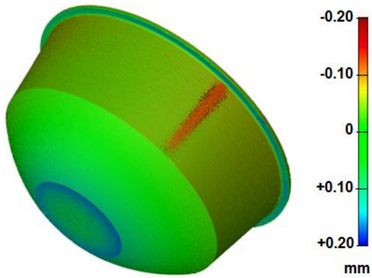

Figure 2: Deviation map of the same component as in in Figure 2, showing the other side of the acetabular cup; a Feldkamp error is visible in red.

Figure 3 shows the wear map obtained from CT measurement of an UHMWPE non-congruous UKP component. The expanded uncertainty of volume measurement obtained in this case was below 0.20% of the sample volume.

All prosthetic components measured by CT were also measured by CMM, for comparing the measurement results. In the case of ceramic prosthetic components, the tactile CMM produced more accurate volume measurements than the CT system. But for polymeric components CT was found capable of more accurate measurements. For instance, Figure 4 shows the wear map obtained from tactile CMM measurements of the UHMWPE non-congruous UKP component whose CT measurements are presented Figure 3; in this case the expanded uncertainty of volume measurement was 0.5% of the sample volume, which is more than the double of the uncertainty obtained by CT measurement.

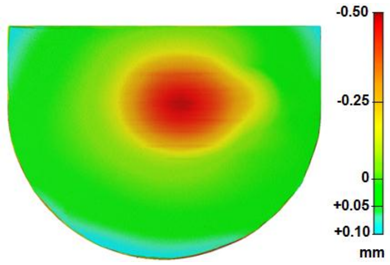

Figure 3: Deviation map showing wear distribution for a polyethylene non-congruous UKP measured by CT system

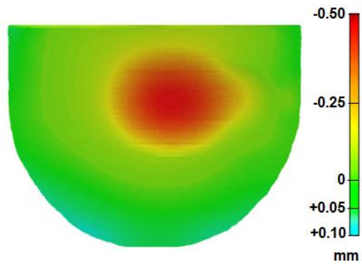

Figure 4: Deviation map showing wear distribution for the same sample as in Figure 3 measured by tactile CMM.

4. Conclusions

This work demonstrated that CT measurements are capable of quantifying wear and deformation of prosthetic components, with volume measurement uncertainty (k=2) below 0.2% of the sample volume, for both ceramic and polymeric components. Comparisons with CMM measurements showed that tactile CMM probing may be more accurate than CT for the measurement of ceramic components. However, tactile CMM suffers of limitations when measuring polymeric components, due to the probing and clamping forces that may influence the measured geometry. In the case of UHMWPE components, CMM measurements were affected by large errors introduced by elastic deformations caused by probing and clamping forces, while CT measurements allowed definitely more accurate wear quantification, with relative uncertainty below 0.2% in the case of CT, against 0.5% in the case of CMM.

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