

# Evaluating hip implant wear measurements by CMM technique

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## ABSTRACT

Wear of the bearing components is a major factor affecting the performance of hip implants. Wear analysis is thus one of the most important processes for understanding of how wear occurs and its location and development, with an aim to improve the success rate and longevity of total hip replacements. This study presents wear measurement and analysis of polyethylene acetabular components using a coordinate measuring machine (CMM). An uncertainty analysis was performed to validate CMM wear measurements. Measurements were made with an increasing number of scanning points on retrieved ex vivo implants to investigate the effect of the number of scanning points on wear measurements. CMM wear measurements were compared to in vivo radiographic measurements (RSA) and volumetric wear estimates made using well-established analytical formulae. The number of scanning points has insignificant effect on wear quantity and measurement uncertainty. CMM linear wear measurements closely match those made using RSA, whereas theoretical volumetric formulae applied to CMM and RSA measurements both appear to overestimate wear volume. The findings further emphasize potential benefit of using CMM ex vivo and RSA in vivo to assess polyethylene wear after total hip replacement surgery. Further, it is shown that identifying key components of the measurement uncertainty are important to improve the accuracy and the reliability of CMM wear measurement.

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## 1. Introduction

Total hip replacement surgery involves damaged bone and cartilage within the hip joint being replaced with artificial components, enabling patients to resume normal functions of the joint. Continuous research and development on design, material and surgical procedure has improved the satisfaction and success rate of this surgery over time. However, wear of the bearing implants is still considered a critical factor that causes aseptic loosening and osteolysis related failures later [1–4]. Therefore, wear analysis is an important tool to understand not only how wear occurs, but also how wear evolves progressively. Such knowledge will enable one to design and develop improved bearing components, thus enhancing the service life of implants. Volumetric and linear wear rates are shown to be two important parameters defining the material loss from the bearing surfaces during their use in the human body. There are a number of wear measurement and estimation techniques used to monitor implant performance in vitro, in vivo and upon retrieval of the implant ex vivo [5–7]. For instance, radiostereometric analysis (RSA) is a sensitive specialized three-dimensional radiographic method that has been widely

adopted to measure prosthesis wear in vivo over the period of implantation. Radiographic methods assume penetration of the femoral head within the acetabular component that represent wear and hence can overestimate the amount of true wear due to early bedding and creep of the polyethylene liner within the metal backed shell [8–10]. Measuring the gravimetric weight of the implant before and after mechanical testing is commonly used to assess wear of implants in vitro during mechanical testing trials [11], but it cannot measure wear in retrieved ex vivo implants whose pre-wear data is unavailable.

Due to its inherent capability and high precision motion accuracy, a coordinate measuring machine (CMM) has recently been used to measure wear of ex vivo implants and is able to trace the wear patch, 3D wear location, depth and volume simultaneously [5,12]. Some guidelines based on standard protocol suggested by ISO 14242-2:2000 have been established and adopted to ensure the acceptable accuracy of CMM measurement [13]. Many studies have investigated the efficacy of CMM wear measurement on implants (hip and knee) both in vitro and ex vivo and reported its potential ability in quantifying minute wear volume with the desired reliability [12,14,15]. CMM relies on measuring a number of scanned points on the worn bearing surface compared to an idealized or unworn surface. Therefore, the number of scanning points that are required to produce accurate wear results is of great interest. ISO 14242-2:2000 specified that the mesh spacing

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between the scanning points must not be greater than 1 mm to achieve an accurate result. Accordingly, researchers have used the mesh grid of  $0.5 \text{ mm} \times 0.5 \text{ mm}$  and/or  $1 \text{ mm} \times 1 \text{ mm}$  for CMM wear measurements [16]. Bills et al. [16] reported that probing of a perfect or ideal sphere with 25 scanning lines and point pitch of 0.5 mm would result in a volumetric wear of as high as about  $346 \text{ mm}^3$ . It must be noted that smaller the point spacing, the higher the number of scanning points and increased subsequent scanning time. While a scanning point distance of less than 1 mm is shown to exhibit an acceptable accuracy of measurements, researchers still have casted doubt about whether there is any potential benefit to consider a fairly large number of scanning points for wear measurements [17], which undoubtedly will increase unnecessary scanning time. In addition to the probing strategy, measurement uncertainty depends on the number of scanning points considered. While volumetric wear estimated by CMM with an uncertainty analysis wear was studied extensively on different number and types of explants, little work focused on a direct investigation of the effect of scanning points on linear and volumetric wear with an expanded uncertainty evaluation. The aim of our study was to (1) measure wear using CMM with a different number of scanning points, (2) compare volumetric wear estimated by CMM with well-known theoretical volumetric formulae and in vivo RSA measurements, and (3) assess expanded uncertainty of CMM measurement with each set of the scanning points.

## 2. Materials and method

### 2.1. Explants

The acetabular component (Longevity XLPE Liner, Zimmer Inc., Warsaw, Indiana, USA) analyzed in this study was retrieved at 1.75 years (one year 9 months) after the implantation. The reasons for the retrieval were due to the infection. According to the supplier, the inner diameter of the component is  $28.15 \pm 0.05 \text{ mm}$ . The explant was cleaned and stored in a temperature and humidity controlled room before the CMM wear measurements were performed.

### 2.2. CMM wear measurements

The process of wear measurement and evaluation presented in this study is shown in Fig. 1. The acetabular component was positioned within the CMM and the unworn region of the component was probed to determine the reference geometry. With respect to the reference geometry, probing the whole inner surface with different scanning points provided actual wear data and enabled the estimation of wear. The result was then validated by identifying the measurement uncertainty to ensure the measurement reliability.

In this study, Brown & Sharpe MicroXcel 7.6.5 coordinate measuring machine manufactured by Hexagon Metrology was used. The machine was connected with measurement software, PC-DMIS, which was used to collect all measurement data accurately for further processing. The automatic probe head of Renishaw TP 20 holds a  $3 \text{ mm} \times 21 \text{ mm}$  straight probe, which has a Ruby contact tip and the head was oriented in a vertical position. The measurement accuracy of the CMM is equal to  $4.5 + 4L/1000 \text{ }\mu\text{m}$ , where  $L$  is the length (in mm) of measurement envelope. The CMM was calibrated in accordance with the requirements of the Hexagon Metrology, which is traceable to the National Standards of Measurement [18]. The CMM was kept in a temperature and humidity control room with the temperature kept at  $20 \pm 1 \text{ }^\circ\text{C}$  and the humidity at  $55 \pm 5\%$ , which is within the limit required for performing high precision

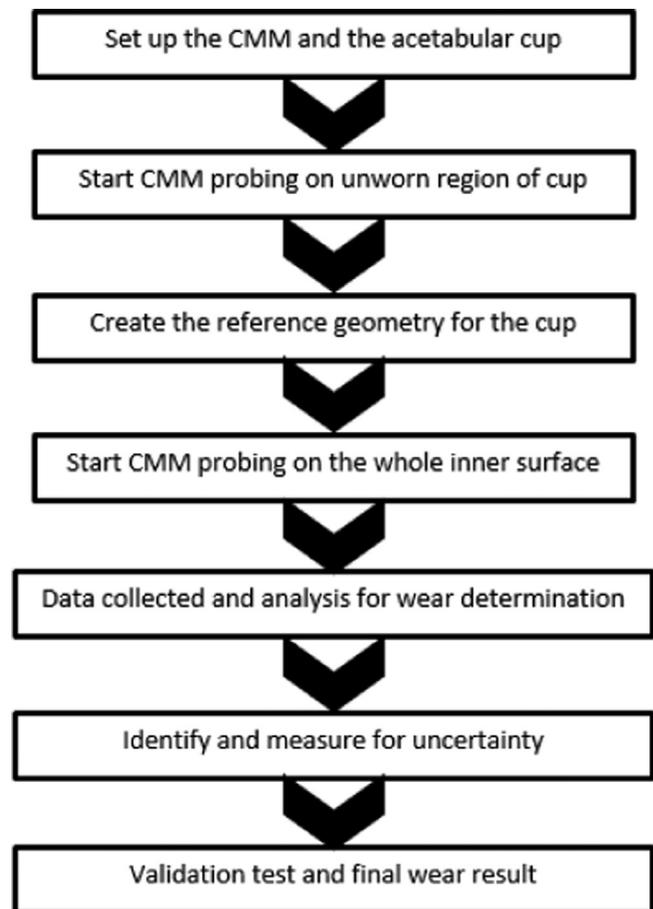


Fig. 1. Flowchart of the wear measurement process.

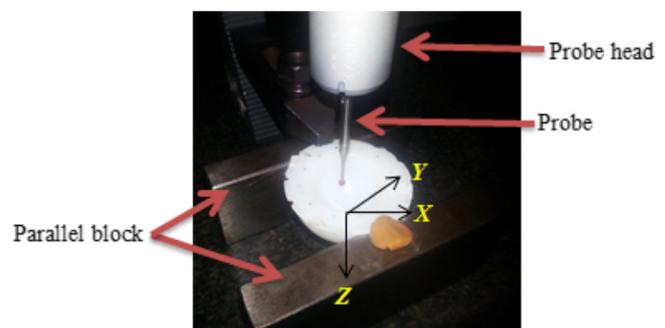


Fig. 2. Setup of the acetabular cup on the CMM.

measurement suggested by the ISO-10360-7:2011. To prevent any unexpected displacement during the probing process and minimize the chance of having unrepeatable results, the acetabular component was set up on the table by holding firmly on two magnetic parallel blocks with a clip and clay as shown in Fig. 2.

Since the pre-wear data of the explanted acetabular component were not readily available, the creation and determination of the reference geometry became very important to help evaluating the actual wear amount. In this study, we have considered 15 random scanning points which will probe on the cup surface for finding the reference geometry. Ten (10) points were taken on the X–Y plane and five (5) points on the Y–Z plane of the cup, as shown in Fig. 2. Each set of the points was used to calculate a sphere and the radius of the calculated sphere was compared with the theoretical size of the cup given by the supplier. If the measured radius of the cup is within the manufacturing tolerance, the center of the

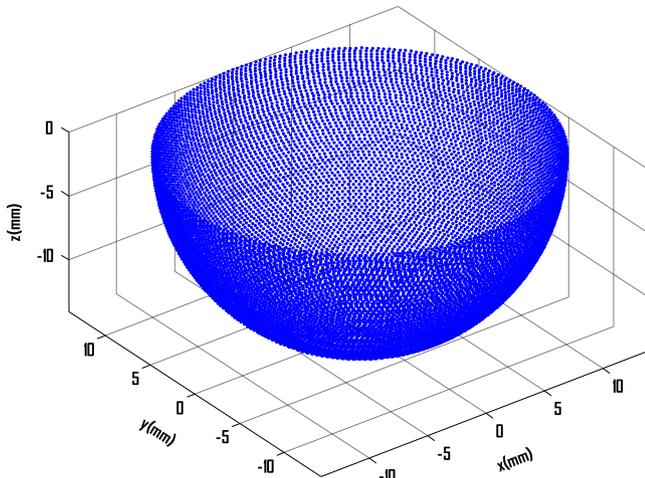


Fig. 3. Representative 3D mesh grid of CMM scanning points on the cup surface.

sphere will set as the origin of the cup. If the measured diameter exceeds the manufacturing tolerance due to more than one or fewer of the probing points are being located on the worn region, the probing process will be repeated with the cup being rotated at a certain interval of the angle about the Z axis until an unworn location/region is found. Similar approach in determining the reference geometry of the explanted cup is eluded in the current author's previous work [15].

Knowing the reference geometry of the cup (i.e. unworn cup), the probing with a certain number of scanning points has been performed on the whole cup surface including worn and unworn regions. In order to investigate the effect of the distribution of the scanning points, we have considered 10,000, 12,000 and 15,000 scanning points for probing the cup surface, in which, the meshing of scanning points with a mesh of 0.25 mm (i.e. the distance between two scanning points) is considered. The distribution of the scanning points for each scanning set was generated by the PC-DMIS software and the whole surface of the explanted cup was automatically probed following the scanning point distribution generated. Fig. 3 depicts a representative meshing of the scanning points on the cup surface. For each probing point, the 3D location was recorded in X, Y and Z coordinates with respect to the origin of the cup estimated. The collected data was then used to calculate the actual wear amount by finding the difference between the reference surface and the actual worn surface of the cup. Due to the wear occurred on the cup surface, each of the actual scanning point location had different distance away from the origin and hence, the radial distance of each point was varied. The radial distance for each scanning point is estimated as:

$$r_{measured} = \sqrt{X^2 + Y^2 + Z^2} \quad (1)$$

where  $r_{measured}$  is the radial distance at each measured point and X, Y and Z are the coordinates of the point. All the measured radii were then used to find the linear wear depth at each scanning point using the following expression:

$$\text{Linear wear depth} = r_{measured} - r_{reference} \quad (2)$$

where  $r_{reference}$  is the radius of the reference sphere. As mentioned previously, mesh grid along the cup surface was generated by the PC-DMIS. In each of the mesh grid, a mean wear depth was calculated by averaging the wear depths of the four corner points of the mesh. The wear volume was estimated by multiplying the mean wear depth with the area of the corresponding mesh grid. The total wear volume was determined by adding wear volume of each grid across the whole cup surface. Further, in order to identify the location of maximum wear depth on the cup, wear vector

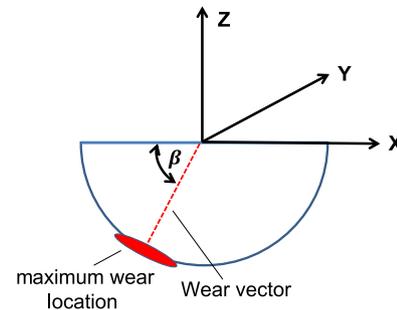


Fig. 4. Definition of wear vector angle.

angle  $\beta$  is determined. As shown in Fig. 4, the wear vector is the vector set from the horizontal plane going through the rim of the unworn cup to the maximum wear location on the cup. In other words, it is the angle between the X-axis and the wear vector, when the cup is looked at on the ZX plane.

### 2.3. CMM measurement uncertainty

Evaluation of uncertainty for a measurement process can create the traceability of the measuring method and confirm the measurement result using CMM. There are a range of sources of uncertainties that impact the CMM measurement. They may include uncertainty that occurs due to the errors of CMM measurement strategy, the probing, determining the reference geometry, the scanning protocol, and computation via software package during post-processing. It is reported that the expanded uncertainty can be effectively evaluated using the suggestion and guideline given in ISO/TS 15530-3:2007, which takes three main uncertainty components into account [19]. Accordingly, the total volumetric expanded uncertainty of CMM,  $U_{CMM}$ , can be written as:

$$U_{CMM} = k \sqrt{(u_{cal}^2 + u_p^2 + u_w^2) + |c|} \quad (3)$$

where  $k$  = the coverage factor, which is assumed to be 2 with a coverage probability of 95%,  $u_{cal}$  = the uncertainty of the calibration of the CMM,  $u_p$  = the uncertainty of the wear measurement procedure,  $u_w$  = the uncertainty of the material and the manufacturing tolerance of the sample, and  $c$  = the systematic measurement errors. Also, the GUM method of uncertainty evaluation involves an uncertainty component due to the surface roughness of the test sample [20]. In this study, it is very difficult to obtain the surface roughness data of the worn acetabular cup without damaging the surface. Therefore, in order to obtain the accurate actual wear measurement, surface roughness measurement for uncertainty evaluation was carefully avoided.

### 2.4. Theoretical formulae for estimating wear volume

As an indirect validation process, the CMM measurements were compared with theoretical wear formulae available in the literature. Previous studies reported different mathematical formulae to estimate the wear of the polyethylene (PE) acetabular component. Notable expressions in this regard are shown in Table 1. Charnley et al. [21] had first introduced an expression for polyethylene (PE) wear volume using a circular cylinder approach. This approach assumes that wear occurred perpendicular to the entrance plane of the cup and as a result this approach overestimates wear volume in the majority of the cases. Kabo et al. [22] takes the direction of wear along the cup opening plane into account in the wear expression. However, Kabo's expression is deemed incorrect identified by researchers and thus is not considered in this paper. Later on, Kosak et al. [23] and Hashimoto along with his coworkers

**Table 1**  
Theoretical formulae to estimate wear volume.

Source of formulae	Mathematical formulae
Charnley et al. [21]	$V_{\text{Charnley}} = \pi r^2 d$
Košak et al. [23]	$V_{\text{Kosak}} = \frac{r^2 d}{2} (\pi + \pi \sin(\beta))$
Hashimoto and coworkers [24]	$V_{\text{Hashimoto}} = \frac{r^2 d}{2} (\pi + 2\beta + \sin(2\beta))$
Ilchmann et al. [25]	$V_{\text{Ilchmann}} = \frac{r^2 d}{2} (\pi + \pi \sin(\beta) + \frac{d}{r} \sin(2\beta)) + 2rf d \cos(\beta)$

(where  $r$ =head radius,  $d$ =maximum wear depth,  $\beta$ =wear vector angle along maximum depth, measured with respect to the cup rim plane and  $f$ =height of cylindrical part)

[24] carefully modified Kabo's expression by considering wear angle. However, their expressions still underestimated actual wear volume. By reviewing all the mathematical formulae, Ilchmann et al. [25] recently introduced a new expression which assumed that the wear would be occurring in a titled angle ( $\beta$ ) with respect to the entrance plane, where the angle  $\beta$  lies between  $0^\circ$  and  $90^\circ$ , and the expression is found to minimize the error in wear estimation.

### 2.5. Clinical wear measurement

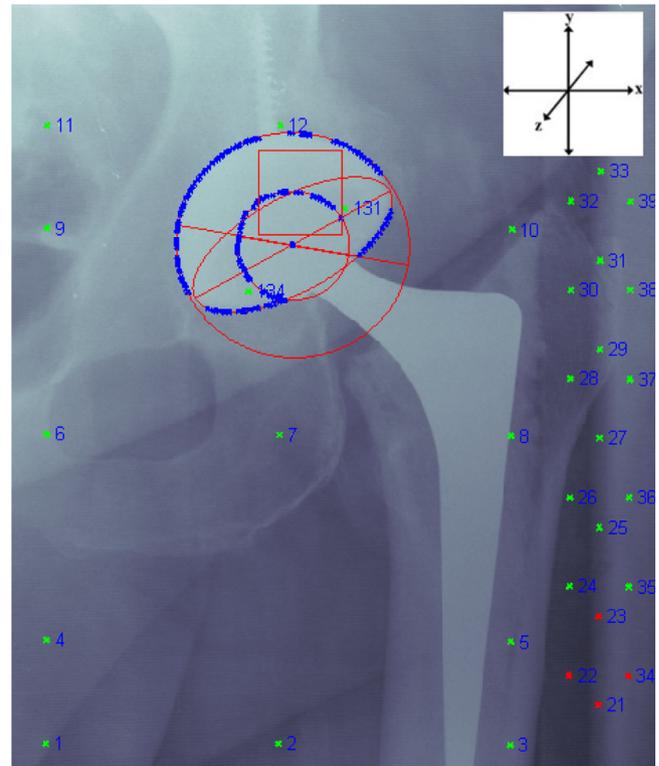
In vivo wear of the component was measured by the standard clinical RSA technique before retrieval of the implant at revision surgery. Initial RSA radiographs were conducted at 4 days after surgery and again at 3 months, 1 year and at 1.75 years prior to retrieval of the implant at revision surgery. The patient was examined in the supine position [26]. RSA radiographs were then examined using UmRSA software (v6.0, RSA Biomedical, Umea, Sweden) and femoral head penetration was measured in relation to the reference segment consisting of the cup ellipse algorithms used in conjunction with the liner beads that were visible in the consecutive radiographs. Two dimensional (2D) and three dimensional (3D) RSA wear measurements were calculated as the movement of the femoral head after one year to exclude bedding-in within the first year [27]. As shown in Fig. 5, 3D wear is estimated as the vectorial sum of medio-lateral ( $X$ -axis), proximal-distal ( $Y$ -axis) and anterior-posterior ( $Z$ -axis) movements of the head. From maximum wear depth location, wear vector angle with respect to the  $X$ -axis was estimated. The 3D RSA measurements in terms of linear and volumetric wear will be compared and discussed with respect to those estimated by CMM technique (to be presented in Section 3.3).

## 3. Results

### 3.1. CMM wear results

Table 2 summarizes the results of wear depth, wear volume, both linear and volumetric wear rate and wear vector angles, along with volumetric uncertainty.

It is seen from Table 2 that the number of scanning points has a negligible effect on linear and volumetric wear, except for the 12,000 scanning points showing a peak of volumetric wear of  $68.0775 \text{ mm}^3$ , which is slightly larger than that for measurements with 10,000 and 15,000 scanning points. Further, the percentage of maximum variation in linear wear and volumetric wear among measurements with 10,000, 12,000 and 15,000 scanning points is 1.6% and 5%, respectively, which is considerably small. This indicates that the number of scanning points of as low as 10,000 are sufficient to capture the wear patches on the cup. Recent study by Langton et al. [28] examined the effect of CMM parameters for

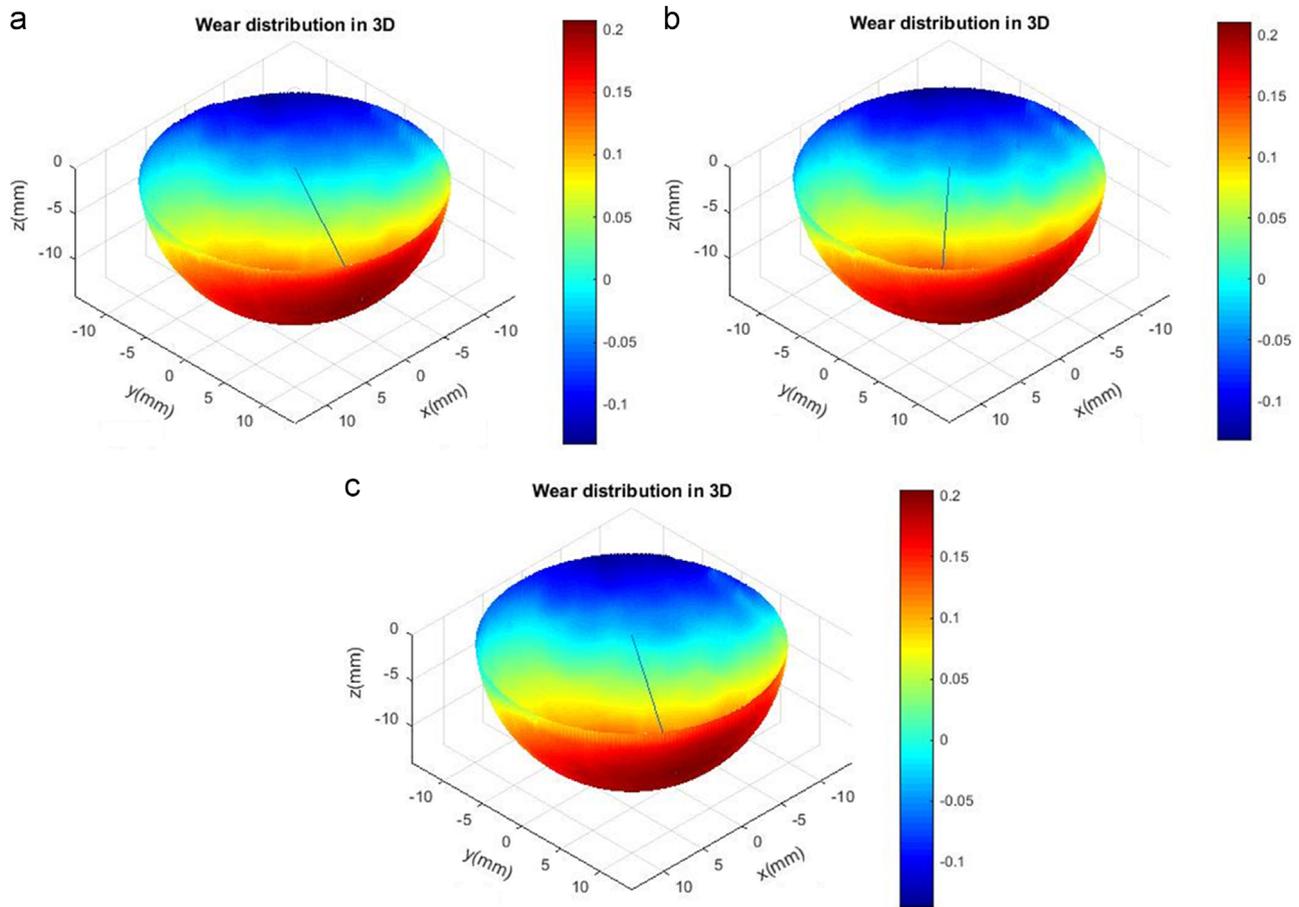


**Fig. 5.** RSA radiographic image of the acetabular component.

ceramic-on-ceramic bearing couple and concluded that the scanning parameters such as point pitch, maximum point to point distance and the number of scanning points had no clinically relevant effect of volumetric wear calculations. Linear and volumetric wear rates shown in Table 2 are estimated by dividing wear amount by the life of the implant which is 1.75 years for the acetabular component considered in this study. Average linear and volumetric wear rates are found to be  $0.12 \text{ mm/year}$  and  $37.18 \text{ mm}^3/\text{year}$ , respectively, which are larger than that reported by other studies. For instance, for an XLPE cup of 28.16 mm diameter for the life of 3 years, linear and volumetric wear rates were reported to be  $0.024 \text{ mm/year}$  and  $4.5 \text{ mm}^3/\text{year}$  [15]. Table 2 shows measured wear vector angle which indicates the location of maximum wear depth or head penetration into the cup. Similar to linear and volumetric wear, wear vector angle varied with respect to the number of scanning points. This indicates that the location of maximum wear depth within wear patch changes slightly with the number of scanning points considered while overall wear amount remains unchanged. The average wear vector angle was found to be approximately  $80.33^\circ$ . Fig. 6 shows wear scar maps highlighting linear wear distribution and wear pattern with color on the cup surface for three different number of scanning points. Colors shown on the wear map represent the actual surface condition of the cup. Referring to the color bar, the colors indicate both positive and negative dimensional change on the cup surface. The positive dimensional change indicates the actual linear wear, where the measured radii were higher than the radius of the reference sphere. The negative dimensional change indicates some deformations on the surface or error occurred. The result further emphasizes the capabilities of CMM to capture localized wear patches or worn areas and hence determine actual 3D wear on explants.

**Table 2**  
Wear measurement result for different number of scanning points.

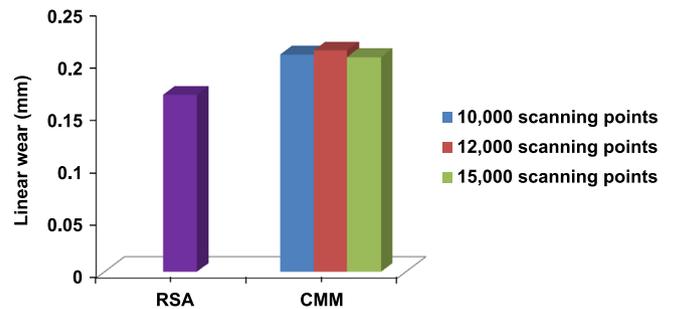
Number of scanning points	Linear wear (mm)	Linear wear rate (mm/year)	Volumetric wear (mm <sup>3</sup> )	Volumetric wear rate (mm <sup>3</sup> /year)	Wear vector angle (deg)	Volumetric uncertainty (mm <sup>3</sup> )
10,000	0.2076	0.1186	64.5396	36.8797	83.9375	0.7679
12,000	0.2113	0.1207	68.0775	38.9014	77.5371	0.7526
15,000	0.2050	0.1172	64.4489	36.8508	79.5226	0.7609



**Fig. 6.** Linear wear distribution on the cup for measurement with: (a) 10,000 scanning points (b) 12,000 scanning points (c) 15,000 scanning points.

**3.2. Uncertainty analysis**

Measurement uncertainty has been estimated for CMM wear measurement tests with each set of scanning points. As highlighted earlier, three main uncertainty components are put into concerned and the total expanded volumetric uncertainty was estimated based on Eq. (3). The uncertainty due to the calibration of the calibrated CMM device  $u_{cal}$  can be found and used directly from the calibration report data supplied from the CMM supplier. The uncertainty value  $u_{cal}$  is given to be 0.0076 mm. The uncertainty caused by the wear measurement procedure  $u_p$  involves the error of the CMM itself during measurements and the error of the scanning probe. This has been estimated by probing a 19 mm diameter high precision artifact 18 times with each set of scanning points, where standard deviation of the difference between theoretical and measured diameter is considered as the uncertainty component, and this is found to be 0.0091 mm. The third uncertainty component  $u_w$  is the uncertainty due to the errors in manufacturing tolerance of the cup. This uncertainty component value is to be found and used directly from the manufacturing data of the acetabular cup, which is 0.2032 mm. The fourth component  $c$  is the uncertainty due to the systematic



**Fig. 7.** Comparison of linear wear estimated by using CMM and RSA techniques.

measurement errors. This is estimated as the difference between the calibrated volume and the mean of 18 volume measurements obtained from 18 repeated measurements of the 19 mm calibration spherical artifact, which is found to be 0.3608 mm<sup>3</sup>. Lastly, the coverage factor  $k$  can be found directly from the CMM calibration report. With the assumption of a confidence level of 95% and the coverage factor of 2, as a representative, the total expanded uncertainty for measurement with 10,000 scanning points was

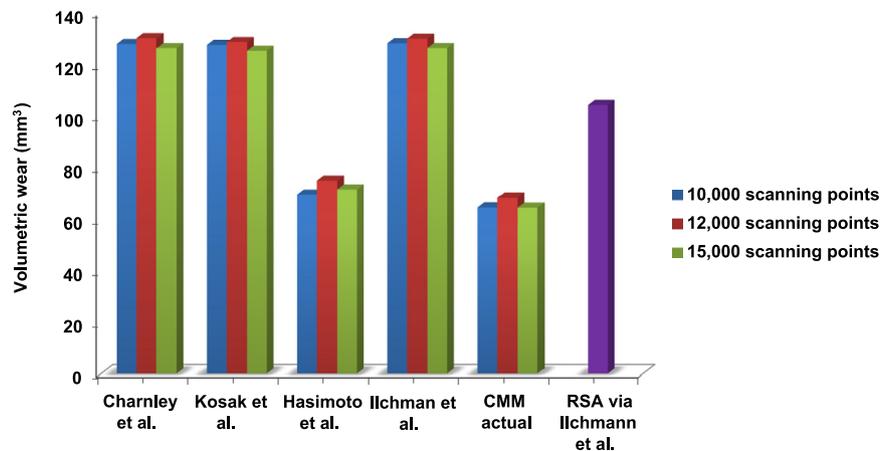


Fig. 8. Comparison of volumetric wear estimated by using CMM, RSA and theoretical formulae.

calculated as:

$$U_{CMM} = 2 \sqrt{\left( (0.0076)^2 + (0.0091)^2 + (0.2032)^2 \right) + |0.3608|} \\ = 0.7679 \text{ mm}^3$$

The above procedure was followed to estimate the expanded uncertainty for measurements with other set of scanning points. Table 2 summarizes the results of uncertainty for measurements with three sets of scanning points. As compared to past CMM wear studies on a PE cup with the same or similar size, the volumetric uncertainty is found to be relatively small, indicating again an acceptable level of confidence of wear measurements by CMM. However, no or little variation in uncertainty for tests with each set of scanning points is observed.

### 3.3. Comparison of CMM measurements with RSA and theoretical formulae

Fig. 7 shows a comparison of linear wear measured by RSA and CMM with three sets of scanning points. It is seen that CMM wear is slightly larger than RSA wear and the percentage of their difference is about 18%, which may be considered reasonably small. This justifies again the acceptable accuracy of CMM wear measurements presented in the paper. This difference may also be due to the small amount of wear that was excluded by RSA measurements as part of the bedding-in and creep process within the first postoperative year.

Fig. 8 shows a comparison of volumetric wear estimated using existing theoretical formulae (as described in Table 1), CMM and RSA techniques. In addition to geometry of head and cup, wear vector angle ( $\beta$ ) and maximum wear depth ( $d$ ) measured by CMM were used in theoretical formulae to estimate wear volume, while RSA linear wear and wear vector angle were used in the Ilchmann et al. formula [25] to estimate RSA volumetric wear. This is an indirect way of determining RSA volumetric wear as RSA technique does not directly provide wear volume.

It is clear from Fig. 8 that all theoretical formulae have over-estimated wear volume, except for Hashimoto et al., as compared to CMM measurement. RSA volumetric wear via Ilchmann et al. is found to be higher than CMM actual. This indicates that theoretical formulae may not be accurate enough to estimate actual wear volume generation given that even actual linear wear depth is known by in vivo RSA approach. Further it is evident that, like CMM measurement, the number of scanning points has a negligible effect of wear volume estimated by theoretical formulae considered in this study. Maximum variation in wear volume between formulae and the CMM is about 30%.

## 4. Discussion

This study is focused on wear measurement and analysis of a retrieved acetabular cup measured using CMM and three sets of scanning points. Previous studies suggested that the cup surface needs to be probed with a sufficient number of scanning points and the meshing of scanning points with a mesh of 0.25 mm (i.e. the distance between two scanning points) or smaller is reasonable to trace the worn surface of the cup. The more the scanning points considered, the more accuracy in geometrically approximating the underlying surface and the traceability of the worn surface, thus providing more accurate wear measurements. However, this hypothesis is not true as confirmed by our results shown in Table 1. Instead, it may be inferred that the number of scanning points more than a certain threshold would not affect much the accuracy of wear measurements; rather it will potentially incur processing time and effort. Such conclusion is very important for situations where mass evaluations of implant components are required at a quicker and more accurate way.

Unlike other existing measurement techniques, for example RSA, where manual intervention and relevant experience are a precursor for wear measurement, the overwhelming benefit of using CMM is its ability to accurately determine unworn surface geometry as the process is much automated without external manipulation. The CMM measurements can be taken with no or little experience of an operator. While the effect of scanning points was found to be insignificant, identification of reference geometry of unworn cup surface is very crucial. A small deviation or misalignment of the reference sphere can cause either over or underestimation of wear amount. The reference geometry enables us to find the origin of the unworn or as-received cup so that wear location and direction can be determined. Previous studies suggested that most of wear occurs away from the pole of the cup because of the inclination angle of the cup during the implantation [17,29]. Therefore, to have a more accurate estimation on location of the cup origin, all the random points must be probed on the unworn regions as much as possible, which are midway between the rim and the pole. The number of iterations for determining reference geometry may be minimized with a proper initial measurement protocol involving cross-check of the underlying deviation or misalignment.

Variation in both linear and volumetric wear rate for different number of scanning points was shown to be insignificant. However, cumulative wear or wear rate obtained by our measurements are shown to be large (Table 1). This could be due to the existing form error due to waviness and roughness of the initial unworn surface. It is assumed that wear was not localized on the surface of

the component but distributed across the surface, and in such case, it is often quite challenging to capture and take the form error into account during identification of reference surface geometry of the component.

The significant difference of wear volume obtained by theoretical formulae and CMM is due to different approaches being used to estimate wear volume. In all mathematical formulae, it is assumed that the head penetrates into the cup with maximum wear depth on a circular contact area on the cup at an angle with respect to the plane of the opening of the cup. Accordingly, we used maximum wear depth and angle obtained from CMM into the formulae to estimate theoretical wear volume. However, wear patch and wear depth may not be located on a circular area but can be distributed on the whole sliding surface of the cup. While theoretical formulae is one dimensional calculation approach and assumes predefined wear geometry on the cup surface with a certain wear depth and angle, thus overestimating wear volume, the CMM traces and locates 3D geometry of every worn area and patch, and hence is able to estimate wear volume more accurately. It must be noted that comparison of CMM wear measurement with theoretical formulae is an indirect way of validation; and hence caution must be taken in interpreting the CMM results presented in this paper. Therefore, the CMM measurements need to be verified with gold standard protocol – gravimetric method, to justify further the efficacy of the measurement approach. In this regard, simple manual wear test on laboratory based polyethylene cup of the size can be done, in which, minute material would be removed from the cup surface by abrasion at a certain interval and weight of worn material would be measured by weighing and accordingly wear volume is recorded. Then the same cup would be measured by the CMM to estimate CMM wear volume and finally both wear volumes would be compared to each other to verify the accuracy of the CMM measurements. Other researchers have considered the similar approach to validate the CMM wear measurements of the metallic explanted cups [16]. RSA is generally accepted as the gold standard of in vivo wear assessment technique and RSA linear wear is shown to closely match with our CMM measurement. However, a direct comparison of CMM wear volume with that of RSA may even not be appropriate as RSA often needs to resort to analytical formulae to estimate wear volume and thus volume results must be interpreted with caution.

The expanded uncertainty is found to be relatively small ( $0.7526\text{--}0.7679\text{ mm}^3$ ) and unaffected by the change of scanning points as well. This is because the test procedure for all measurements is pretty much same and the number of scanning points considered is probably large enough to capture the worn geometry accurately while repeating the measurements. Such uncertainty apparently looks reasonable to endorse the reliability of CMM measurement; however, as wear amount gets further smaller and minute due to advances in new material and design of implants, this value may be excessive. The overall uncertainty can further be minimized by reducing uncertainty of CMM probing and determining reference geometry. CMM probing uncertainty can be minimized by designing and developing a more accurate and high precision machine while uncertainty due to misalignment error in identifying reference sphere can be reduced by carefully locating unworn areas and determining initial form error due to manufacturing faults. Similar issues in relation to minimizing uncertainty errors in CMM measurements have been addressed by others [5,30]. It is to be noted that in this study, only one explant is taken for measurement analysis and evaluation. To improve the reliability and the accuracy of measurement process and subsequent results, wear measurements on multiple explants might be considered. On the same note, it can, however, be cautiously said that the CMM wear measurement process, uncertainty

analysis and validation with RSA clearly prove that the result and conclusions presented in the paper are still reasonable and valid.

## 5. Conclusions

Wear measurement and analysis is important to monitor the wear occurrence, wear location and wear development of current hip implants. This paper has presented an evaluation of CMM wear measurement with a particular focus on the effect of scanning points. Linear and volumetric CMM wears were compared with RSA and theoretical formula calculations. An expanded uncertainty evaluation for CMM measurements with each set of scanning points was estimated. No noticeable change in linear and volumetric wear was observed for CMM tests with 10,000, 12,000, and 15,000 scanning. This indicates that while it is true that the number of scanning points for CMM probing should be large enough to capture the worn geometry of the cup; but the number of scanning points should be optimized so that it does not increase additional probing time while ensuring acceptable level of measurement accuracy with a lower volumetric certainty. CMM wear results showed that it is possible to estimate linear and volumetric wears with an expanded volumetric uncertainty of as low as  $0.7609\text{ mm}^3$ , exhibiting the reliability and confidence of CMM measurements. In this case example, linear wear matches closely with RSA measurements within a percentage of difference of 18%. Analysis of results showed that existing theoretical formula overestimated volumetric wear compared to CMM wear volume. RSA wear volume estimated via a theoretical formula was found to be still larger than CMM wear volume.

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## References

- [1] D.H. Sochart, Relationship of acetabular wear to osteolysis and loosening in total hip arthroplasty, *Clin. Orthop.* 363 (1999) 135–150.
- [2] D.J. Langton, S.S. Jameson, T.J. Joyce, N.J. Hallab, S. Natu, A.V.F. Nargol, Early failure of metal-on-metal bearings in hip resurfacing and large-diameter total hip replacement, *Bone Jt. J.* 92-B (1) (2010) 38–46.
- [3] T. Rossler, D. Mandat, J. Gallo, M. Hrabovsky, M. Pochmon, V. Havranek, Optical 3D methods for measurement of prosthetic wear of total hip arthroplasty: principles, verification and results, *Opt. Express* 17 (15) (2009) 12723–12730.
- [4] J.H. Dumbleton, M.T. Manley, A.A. Edidin, A literature review of the association between wear rate and osteolysis in total hip arthroplasty, *J. Arthroplast.* 17 (5) (2002) 649–661.
- [5] P.J. Bills, R. Racasan, R.J. Underwood, P. Cann, J. Skinner, A.J. Hart, X. Jiang, L. Blunt, Volumetric wear assessment of retrieved metal-on-metal hip prostheses and the impact of measurement uncertainty, *Wear* 274–275 (2012) 212–219.
- [6] S. Carmignato, E. Savio, Traceable volume measurements using coordinate measuring systems, *CIRP Ann. Manuf. Technol.* 60 (1) (2011) 519–522.
- [7] R.W. McCalden, S.J. MacDonald, C.H. Rorabeck, R.B. Bourne, D.G. Chess, K. D. Charron, Wear rate of highly cross-linked polyethylene in total hip arthroplasty. A randomized controlled trial, *J. Bone Jt. Surg. Am.* 91 (4) (2009) 773–782.
- [8] T. Ilchmann, M. Lüem, S. Pannhorst, M. Clauss, Acetabular polyethylene wear volume after hip replacement: reliability of volume calculations from plain radiographs, *Wear* 282–283 (2012) 69–75.
- [9] D.W. Manning, P.P. Chiang, J.M. Martell, J.O. Galante, W.H. Harris, In vivo comparative wear study of traditional and highly cross-linked polyethylene in total hip arthroplasty, *J. Arthroplast.* 20 (7) (2005) 880–886.
- [10] R.W. McCalden, D.D. Naudie, X. Yuan, R.B. Bourne, Radiographic methods for the assessment of polyethylene wear after total hip arthroplasty, *J. Bone Jt. Surg. Am.* 87 (10) (2005) 2323–2334.

- [11] M.D. Ries, M.L. Scott, S. Jani, Relationship between gravimetric wear and particle generation in hip simulators: conventional compared with cross-linked polyethylene, *J. Bone Jt. Surg. Am.* 83 (2 suppl. 2) (2001) S116–S122.
- [12] M. Spinelli, S. Carmignato, S. Affatato, M. Viceconti, CMM-based procedure for polyethylene non-congruous unicompartmental knee prosthesis wear assessment, *Wear* 267 (5–8) (2009) 753–756.
- [13] ISO 14242-2: 2000, Implants for Surgery – Wear of Total Hip Joint Prostheses – Part 2: Methods of Measurement, 2000.
- [14] B. Morris, L. Zou, M. Royle, D. Simpson, J.C. Shelton, Quantifying the wear of acetabular cups using coordinate metrology, *Wear* 271 (7–8) (2011) 1086–1092.
- [15] M.S. Uddin, Wear measurement and assessment of explanted cross-linked pe acetabular cups using a CMM, *Tribol. Trans.* 57 (5) (2014) 767–777.
- [16] P. Bills, L. Blunt, X. Jiang, Development of a technique for accurately determining clinical wear in explanted total hip replacements, *Wear* 263 (7–12) (2007) 1133–1137.
- [17] J.K. Lord, D.J. Langton, A.V.F. Nargol, T.J. Joyce, Volumetric wear assessment of failed metal-on-metal hip resurfacing prostheses, *Wear* 272 (1) (2011) 79–87.
- [18] ISO/FDIS 10360-7:2011, Geometrical Product Specifications (GPS) – Acceptance and Reverification Tests for Coordinate Measuring Systems (CMS) – Part 12: Articulated Arm Coordinate Measurement Machines (CMM), 2011.
- [19] ISO/TS 15530-3:2007, Geometrical product specifications (GPS). Coordinate measuring machines (CMM). Technique for determining the uncertainty of measurement. Use of Calibrated Workpieces or Standards, 2007.
- [20] JCGM 100, Evaluation of Measurement Data – Guide to Expression of Uncertainty In Measurement (GUM 1995 with minor corrections), JCGM, 2008.
- [21] J. Charnley, A. Kamangar, M.D. Longfield, The optimum size of prosthetic heads in relation to the wear of plastic sockets in total replacement of the hip, *Med. Biol. Eng.* 7 (1) (1969) 31–39.
- [22] J.M. Kabo, J.S. Gebhard, G. Loren, H.C. Amstutz, In vivo wear of polyethylene acetabular components, *J. Bone Jt. Surg. Br.* 75 (2) (1993) 254–258.
- [23] R. Kosak, V. Antolic, V. Pavlovic, V. Kralj-Iglic, I. Milosev, G. Vidmar, A. Iglic, Polyethylene wear in total hip prostheses: the influence of direction of linear wear on volumetric wear determined from radiographic data, *Skelet. Radiol.* 32 (12) (2003) 679–686.
- [24] C.J. Sychterz, K.H. Moon, Y. Hashimoto, K.M. Terefenko, C.A. Engh, T.W. Bauer, Wear of polyethylene cups in total hip arthroplasty. a study of specimens retrieved post mortem, *J. Bone Jt. Surg. Am.* 78 (8) (1996) 1193–1200.
- [25] T. Ilchmann, M. Reimold, W. Müller-Schauenburg, Estimation of the wear volume after total hip replacement. A simple access to geometrical concepts, *Med. Eng. Phys.* 30 (3) (2008) 373–379.
- [26] C.R. Bragdon, J. Thanner, M.E. Greene, H. Malchau, G. Digas, W.H. Harris, J. Kärrholm, Standing versus supine radiographs in RSA evaluation of femoral head penetration, *Clin. Orthop.* 448 (2006) 46–51.
- [27] S.A. Callary, L.B. Solomon, O.T. Holubowycz, D.G. Campbell, Z. Munn, D. W. Howie, Wear of highly crosslinked polyethylene acetabular components, *Acta Orthop.* 86 (2) (2015) 159–168.
- [28] D.J. Langton, R.P. Sidaginamale, J.P. Holland, D. Deehan, T.J. Joyce, A.V.F. Nargol, R.D. Meek, J.K. Lord, Practical considerations for volumetric wear analysis of explanted hip arthroplasties, *Bone Jt. Res.* 3 (3) (2014) 60–68.
- [29] A. Jedenmalm, F. Nilsson, M.E. Noz, D.D. Green, U.W. Gedde, I.C. Clarke, A. Stark, G.Q. Maguire, M.P. Zeleznik, H. Olivecrona, Validation of a 3D CT method for measurement of linear wear of acetabular cups, *Acta Orthop.* 82 (1) (2011) 35–41.
- [30] X.Q. Hu, C.M. Han, R.J.K. Wood, A geometric method to measure the wear of hip joint, *Wear* 271 (11–12) (2011) 2775–2781.