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The surface topography of retrieved femoral heads

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Excessive wear of UHMWPE sockets is considered detrimental to the long-term performance of total hip replacement procedures. Although many factors contribute to the wear process, laboratory experiments have indicated that one of the most important factors affecting the wear rate is surface topography and in particular, the arithmetic mean surface roughness, R_a, of the hard counterface. Surface roughness values were therefore obtained from the heads of 37 explanted and five new Charnley prostheses. The surface topography was measured using a Rodenstock RM 600 non-contacting profilometer. Five parameters were used to give a quantitative characterization of the surface texture; arithmetic mean surface roughness, R_a, root mean square (RMS) surface roughness, R_q, peak to valley height, R_t, average single peak to valley height from five adjoining sample lengths, R_z, and the skewness of the height distribution, *Sk*. Further, qualitative investigations were undertaken using a Joel-JSM-IC848 scanning electron microscope (SEM). The median values of R_a, R_q, R_t and R_z for explanted heads showed statistically significant increases when compared with values from new prostheses. No significant difference was found between any of these parameters measured in the anterior–posterior and the medial–lateral directions. This result may have important implications for the design of joint simulators. No correlation was found between any of the parameters and implant period.

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1. Introduction

The excessive wear of ultra-high molecular weight polyethylene (UHMWPE) components is almost universally regarded as being detrimental to the performance of the total joint replacement procedure. The wear process can lead to a degradation in performance due to biomechanically and/or biologically induced changes which ultimately lead to prosthetic loosening [1–5]. This is especially true of total hip arthroplasty (THA). Laboratory evidence has shown that changes in the surface topography, especially the average surface roughness, R_a, of a hard counterface is an important feature in the wear of UHMWPE [6–8]. However, little work has been published on the other parameters that describe the surface texture of orthopaedic bearing surfaces or on changes that occur during implantation.

The surface topography can be investigated quantitatively using either contacting or non-contacting profilometry [9–11]. Contacting profilometry is well established, particularly in quality control applications where international standards exist for the measurement of surfaces using these devices. The second category covers a multitude of devices whose common feature is that they do not requre physical contact with the surface under investigation. Profilometers of this kind include atomic force microscopes (AFM) [12], scanning tunnelling microscopes (STM) [13] and optical devices [9]. The latter class of devices include those based on interferometry, focus error detection, or scanning confocal microscopy. These non-contacting profilometers are considered advantageous in situations where the surfaces may be prone to distortion or damage by the stylus of a contacting device.

Qualitative work on the surface texture of explanted femoral heads has highlighted the multidirectional nature of the scratches created during the period of implant [14–16]. However, no quantitative assessment was undertaken to determine whether or not a preferential scratch direction existed. Wroblewski *et al.* [17] investigated the surface roughness of four femoral heads of stems which had been removed because of loosening or fracture, but in which the corresponding sockets had remained well fixed. Each had been implanted for 20 years or more. The mean penetration rate of the sockets was 0.022 (± 0.013) mm/years and as such constituted a particularly low

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rate of wear. The average surface roughness, R_a, of the explanted femoral heads was 0.034 μm compared with 0.019 μm for new ones. The R_a values measured in the coronal plane were greater than those in the sagittal plane for three of the four heads and therefore may indicate a preferential scratch direction. Issac *et al.* [18] investigated the surface roughness of 35 Charnley heads, using a Rotary Talysurf 4. The maximum value of the arithmetic mean surface roughness (R_a) from a number of scans across each specimen was recorded. It was reported that the mean of this maximum surface roughness was equal to 0.068 μm compared with the R_a value found on new prostheses of 0.02 μm. A larger study involving 71 Charnley femoral heads, again by Issac *et al.* [19], reported similar results with a mean of 0.053 μm and a range from 0.013 to 0.4 μm. However, unlike laboratory studies, no strong correlation was found between the femoral head roughness, as measured by R_a, and the penetration rate. The causes of such a poor correlation may include the fact that, unlike *in vitro* experiments, the average surface roughness is not uniform over the femoral head or that the temporal variations in the surface topography on the femoral head were unknown. Further reasons for this lack of correlation, not specified in the published article, are that no assessment of the contributions to wear from third-body processes were possible and that the effects of other surface parameters on the wear rate were not considered. Recently, Bauer *et al.* [20] have used a Zygo Maxim-3D interferometric microscope to investigate the surface texture of explanted CoCr femoral heads. The median R_a and peak to valley heights, R_t, were reported as 0.035 μm (range: 0.008–0.47 μm) and 0.577 μm (range: 0.292–4.158 μm), respectively.

The aim of this research was to investigate the surface topography on a series of explanted Charnley femoral heads. In particular, the differences in the roughness values in the medial–lateral (M–L) and anterior–posterior (A–P) directions was explored using both qualitative and quantitative techniques. The variation of the five roughness parameters with the period of implant was also investigated.

2. Experimental procedure

Thirty-seven Charnley femoral stems were removed at revision surgery at the Centre for Hip Surgery, Wrightington Hospital. The femoral heads were made from 316L or Ortron 90 stainless steel. All the prostheses were originally fixed with cement. A brief summary of the clinical details is given in Table I. Table II gives the reasons for primary THR and the operative findings at the revision surgery.

TABLE I Clinical and patient information relating to the explanted total hip replacements

Parameter	Value
Age at primary (years)	54 ± 14 (37 obs)
Implant period (years)	12.1 ± 4.6 (37 obs)
Weight (N)	710 ± 150 (35 obs)
Sex	16 female : 21 male

TABLE II Reason for primary arthroplasty and operative findings at revision surgery

Reason for primary surgery	Operative findings at revision
12 single osteoarthritis	19 loose stem + loose cup
9 bilateral osteoarthritis	6 loose cup
4 rheumatoid arthritis	2 infection + loose cup
12 others	10 others

A random sample of 10 of the 37 femoral heads were examined using a Joel-JSM-IC848 scanning electron microscope (SEM). Prior to examination using the SEM, the specimens were cleaned in a solution of Neutrocon using an ultrasonic bath. The specimens were placed in the vacuum chamber of the SEM such that the axis of the head was in the vertical position. Electron micrographs were recorded of any interesting surface features.

Quantitative assessment of the surface topography was achieved by using a Rodenstock RM 600 profilometer at the National Physical Laboratory (NPL) [9]. The device works using the focus error detection principle [21]. Errors in focussing the laser beam on to the surface under study are recorded by a series of four photodiodes in what is called the pupil obscuration method. A servo-controlled system adjusts the objective lens until the focus error is zero. This adjustment is then interpreted as a change in height of the surface. A profile of the surface is achieved by scanning in either the x or y directions.

The contact region between the socket bore and the femoral head was deduced from the calculated wear direction [22] and the orientation of the socket deduced from radiographs. All the surface profiles of the explanted femoral heads were taken within this region. Ten scans were taken in each of the A–P and M–L directions. Each profile consisted of a 1.4 mm evaluation length, l_e, with a cut-off of 0.2 mm and consisted of 770 sampling points. The focus error profilometer may produce slightly different values from those gained from other devices. These differences can be quantified with the aid of a wavelength–amplitude space diagram devised by Steadman [23, 24]. Five parameters describing the surface topography were investigated.

The reasons for the recording of these five surface parameters, rather than any of the others that were available, were as follows:

(1) Arithmetic mean surface roughness, R_a, was included in the set since it is the one parameter which is almost universally used in describing surface roughness, especially with relation to laboratory wear tests [25]. The average surface roughness is defined as [26, 27]:

$$R_a = \frac{1}{l}\int_0^l |z|\,dx \qquad (1)$$

Here l is the sampling length, although in practice the average of a number of sampling lengths within one evaluation length, l_e, is recorded [26] and z is the profile height relative to the mean line. The

R_a parameter is used to define the maximum surface roughness of hip replacement bearing surfaces in British Standard, BS 7251, part 4 [28].

(2) Root mean square (RMS) roughness, R_q, was included as it is often used as an alternative to R_a. The parameter gives a greater weighting to the larger deviations from the reference line and therefore gives larger numerical values than the equivalent R_a value. The mathematical definition of R_q is [26, 27];

$$R_q = \sqrt{\frac{1}{l}\int_0^l z^2\,dx} \tag{2}$$

(3) The inclusion of the peak to valley height, R_t, [26, 27] was partly on the basis of the work undertaken by Dowson *et al.* [29] which indicated the significant role counterface imperfections have on the wear of the polymeric surface. However, this parameter does not distinguish between high peaks and deep valleys. Further, it is often quoted when surface topography measurements are undertaken using interferometric devices.

(4) The mean peak to valley height, R_z, was incorporated for similar reasons to those given for R_t. R_z is defined by the following equation [26, 27]:

$$R_z = \frac{1}{5}\sum_{l_e=1}^{5} R_{zl_e} \tag{3}$$

The value of R_z is less affected by the extremes of the profile than R_t, especially if the profile is not homogenous.

(5) The previous four parameters give no information on the shape of the amplitude distribution function. The skewness of the amplitude distribution function, which is a measure of this function's asymmetry, indicates whether or not there are a disproportionate number of high peaks or deep valleys. It is defined as [26];

$$Sk = \frac{1}{(R_q)^3}\int_{-\infty}^{\infty} z^3 p(z)\,dz \tag{4}$$

Here $p(z)$ is the probability density function given that a profile height occurs between the heights z and $(z + dz)$.

Graphical representation of the surface roughness parameters are given in Fig. 1.

The results are averages from each of the set of 10 profiles. Each set of results was checked for normality using the test described by D'Agostino *et al.* [30, 31] and standardized normal probability plots. Agreements between the results gained from the A–P and M–L directions were undertaken using the method proposed by Bland and Altman [32]. Spearmans rank correlation was used in determining the extent of association between the five measured roughness parameters and the time of implantation.

3. Results

Investigation of the femoral head surface using the SEM revealed multidirectional scratching (Fig. 2). Both from a visual inspection and from the SEM micrographs, the changes in topography were not uniform across the surface (Figs 2 and 3), even in areas which were considered to be part of the contact zone. Scratch widths varied between the resolution of the SEM, at the magnifications used, to approximately 10 μm (Fig. 4). Areas between scratches were relatively unscathed with limited changes in the surface topography (Fig. 3). The heads of the new Charnley prostheses showed no discernible defects at the magnifications used except for marks formed during polishing.

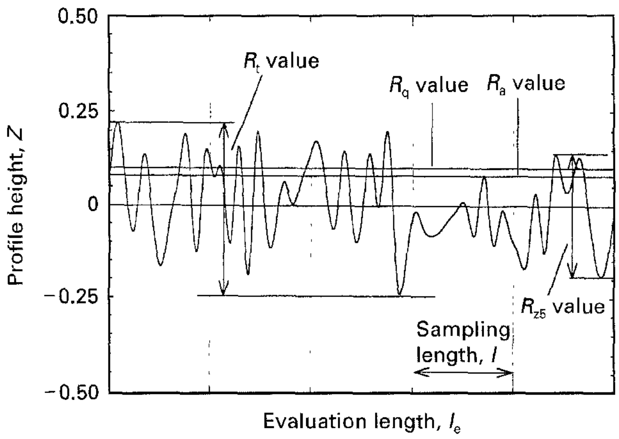

Figure 1 Graphical representation of the surface roughness parameters used in this investigation.

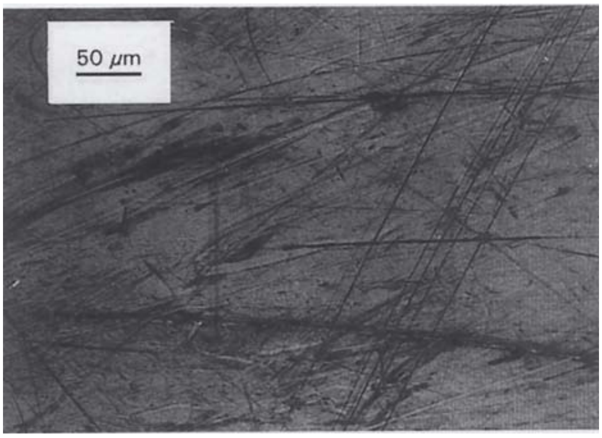

Figure 2 Micrograph indicating the random nature of the scratch directions.

The mean error and limits of agreements of the five roughness parameters were calculated by analysing the data from both the A–P and M–L directions, for each of the retrieved prostheses (Table III). Further, graphs of the values in each of the directions were plotted (Fig. 5) as were the differences in the values of the matched pairs versus their average values (Fig. 6). No statistically significant difference was detected in the bias of each of the parameters (matched pairs *t*-test). No structure to the distribution of the residuals was recorded, on a qualitative level, for each of the five variables.

The overall median values of the surface parameters, combining both the A–P and M–L directions are displayed graphically, in the form of a box and whisker plot, in Fig. 7. These values are compared to

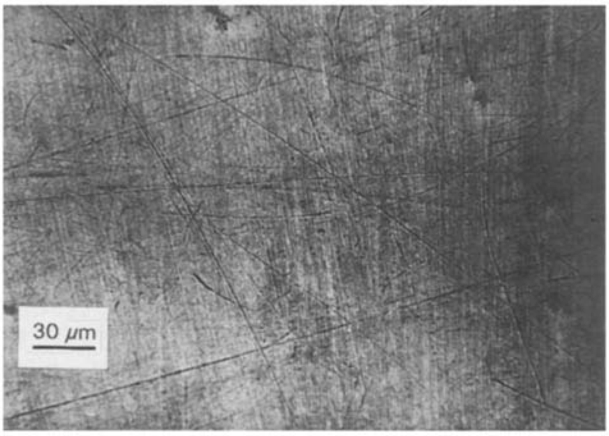

Figure 3 Micrograph showing the reduction in scratch density with respect to Fig. 2.

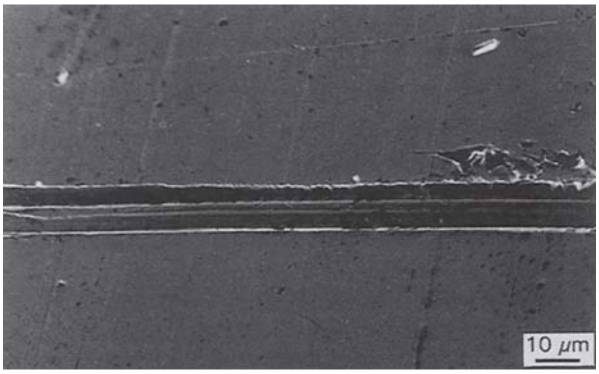

Figure 4 Micrograph showing the approximate upper limit of the scratch width. Note the piled up material either side of the indent.

TABLE III Comparison of surface roughness parameters in the A–P and M–L directions. No statistical significance in the bias or any systematic differences between the parameters in the A–P and M–L directions

Surface Roughness Parameter	Residuals Bias [f(A–P)–f(M–L)]	Limits of Agreement
R_a (μm)	0.00	– 0.05–0.05
R_q (μm)	0.00	– 0.08–0.08
R_t (μm)	– 0.04	– 0.92–0.84
R_z (μm)	– 0.02	– 0.41–0.37
Sk	– 0.24	– 3.87–3.39

those found from measuring new prostheses (Table IV). All the parameters, except the skewness, showed a statistically significant difference (Wilcoxon rank-sum test) in that the *in vivo* environment caused an increase in the surface roughness. It should also be noted that the relative increases in R_t and R_z are greater than those for R_q and R_a.

No correlation between any of the roughness parameters and the implant period was observed. A representative plot of average surface roughness, R_z, versus implant period, T, is shown in Fig. 8.

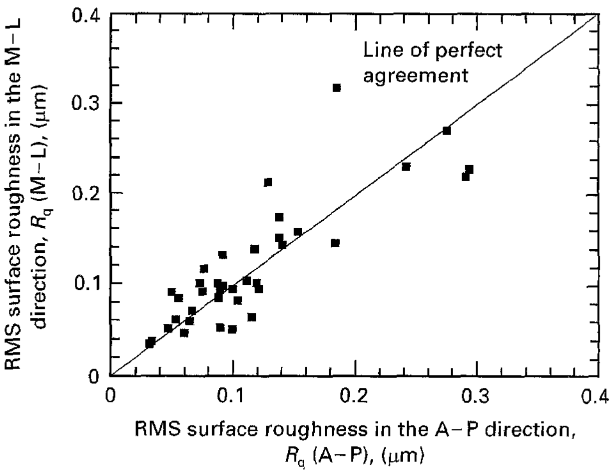

Figure 5 Comparison of the R_q values measured in the A–P and M–L direction.

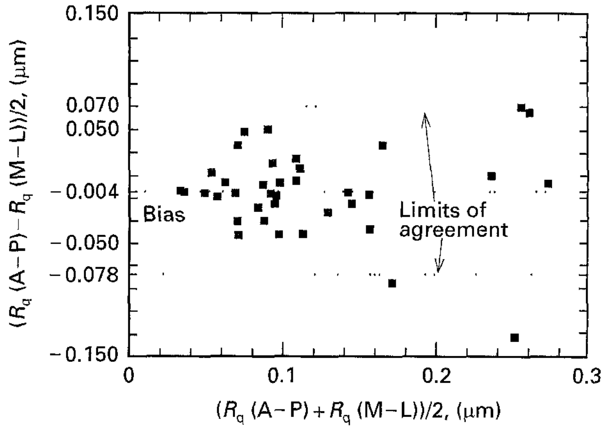

Figure 6 Plot of the error versus the average value of the parameter R_q for the data displayed in Fig. 5.

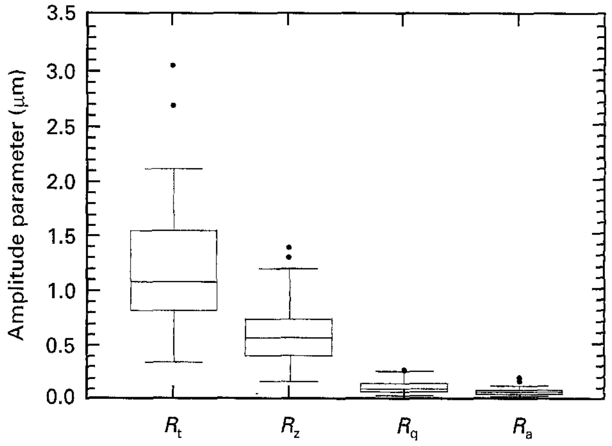

Figure 7 Distributions of the four amplitude parameters measured from the explanted specimens.

4. Discussion

In accordance with previous surveys of retrieved femoral components, these results indicate that the *in vivo* environment causes appreciable damage to the surface of the femoral head. All the amplitude parameters, $R_i (i = a, q, z$ or $t)$, showed significant increases of between three and four times the corresponding values

TABLE IV Comparison of roughness values between new and explanted prostheses

Parameter	New	Explanted
R_a^* (μm)	0.02 (0.02 ± 0.01)	0.06 (0.07 ± 0.04)
R_q^* (μm)	0.03 (0.04 ± 0.02)	0.09 (0.12 ± 0.06)
R_t^* (μm)	0.27 (0.33 ± 0.23)	1.1 (1.3 ± 0.6)
R_z^* (μm)	0.13 (0.16 ± 0.08)	0.56 (0.63 ± 0.32)
Sk	− 0.46 (− 0.45 ± 0.81)	− 0.27 (− 0.50 ± 1.4)

* Statistically significant difference between the median values for new and explanted prostheses (Wilcoxon rank-sum test: $p < 0.001$).

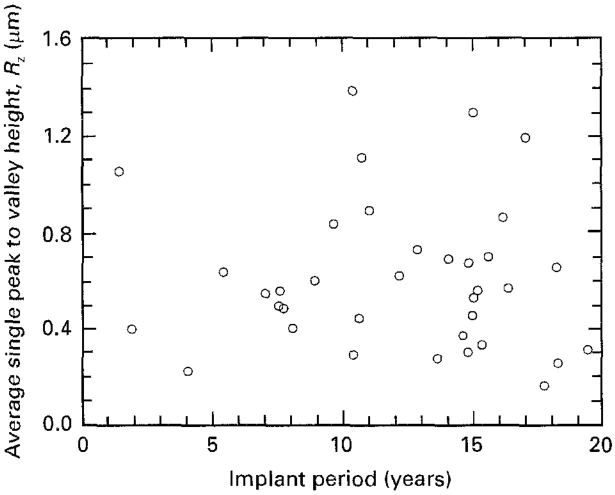

Figure 8 Plot of R_q versus implant period, T_r.

for new heads which are currently available. Of greater benefit would have been the surface roughness values of each of the heads prior to the primary operation, but this had not been undertaken, due to the extended period of implantation. Therefore the exact increase for each femoral head surface cannot be calculated. This was also true for previous studies [17–20]. However, the fact that all the prosthetic heads had a mirror finish prior to implantation sets an upper limit on the values of the surface roughness. It can be concluded therefore, that these results may not be as overwhelming as matched pairs of data might have been, but the general result that a significant increase in surface roughness occurs during implantation appears to be beyond doubt. It is probable that an increase in the roughness of this magnitude may increase the wear of the UHMWPE bearing surface.

From the SEM studies it was apparent that the roughening of the femoral head was not uniform. This is reflected in the larger increases in the parameters R_t and R_z relative to R_q and R_a. The reason for this is that the latter two parameters include a process of integration along the profile and will therefore include parts which are relatively unscathed. Ingression of bone cement is considered to be the principal agent in causing damage to the femoral surface *in vivo* [33]. Laboratory tests have substantiated this and in particular have noted the role of the radio-opaque additives [34, 35].

SEM inspection of the explanted femoral heads tended to reflect the results previously cited in the literature [14–16]. In particular, the multidirectional nature of the scratches was apparent when using the SEM and from the profilometer results. The major motion of the hip is in flexion–extension and therefore intuition would suggest that the majority of scratches would have an A–P orientation. As a consequence the surface roughness measured in the M–L direction would be greater than that recorded in a set of A–P profiles. A number of reasons may contribute to the fact that this is not found to be the case. First, the particular motions that produce a disproportionately large amount of scratching, due to a large joint reaction force, may not be those of the flexion–extension type. Secondly, the evaluation lengths of the profiles are 1.4 mm. Thus parameters taken from the profiles will be averages taken from different areas of scratching which may have different preferred orientations at a local level. Further, due to the fact that the profile will include parts of the head which are undamaged, less weighting will be given to the effects of scratching than is the case for measuring the scratched zones only. Lastly, the spatial resolution of the profilometer in the horizontal plane (~2.0 μm) may fail to record the finer scratches. This is compounded by the fact that the scratching is non-uniform. Thus, any information due to preferential scratching, in scratches with widths of the order of 1 μm or less, may be lost.

The observation that there is no statistically significant difference between the values measured in the A–P and M–L directions has important implications in that the orientation of the scratch relative to the motion vector is influential in terms of the wear rate [29]. If the surface of an implanted head is scratched for a sizeable portion of the implant period, then a significant proportion of the scratches will have a component perpendicular to the motion direction due to their random orientation. The contribution to the wear rate from this orientation will tend to be greater than if the scratch directions were solely parallel to the motion. Simple simulators and practically all pin-on-plate machines have motion loci such that scratches that are formed during the test remain parallel to the velocity vector. As a consequence, they may give a poorer representation of *in vivo* behaviour. A counter argument to this line of thought is that simulators should represent the best possible environment, in that no or minimal scratching of the femoral surface should occur, since this is then a unique reference about which test results can be compared. In such a situation, scratching may indicate the ingression of contaminants between the bearing surfaces and, as a consequence make the test invalid. However, a small amount of scratching may arise from deterioration in the surface due to oxidative processes or particulates within the UHMWPE itself [36]. It is this idea that a certain amount of scratching can occur, not through external contaminants, but through the release of third-body particles from the test components themselves that makes accurate representation of the motion cycles found *in vivo* a high priority.

Two theories can be put forward to explain the observation that there was no correlation of any of the roughness parameters with respect to implant period. The first possible explanation is that the differences between specimens in the amount of material, principally bone cement, found in the joint space and which was available for scratching the surface, is so great as to mask any correlation of temporal changes in surface roughness. Secondly, the process itself may not be gradual but occur in a few brief periods throughout the lifetime of the procedure.

5. Conclusions

Substantial damage to the femoral head occurs *in vivo*. The damage tends to be localized and in the form of scratches. No overall preferred scratch direction was detected either from the SEM observations or from the profilometry. This result may have important implications in terms of the motion loci in simulators. The lack of correlation between any of the parameters and the implant period may indicate one of two possibilities; first, that the amount of material found in the joint space varies enormously between patients or, secondly, that the roughness increase is not a gradual process. Further studies are being undertaken, at present, to quantify the amount of bone cement within the joint space and then correlate this and other parameters with the wear of the acetabular component.

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