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Evaluation of fretting wear on the femoral stem surface

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ABSTRACT. *Fretting wear on polished femoral stems has been well documented in clinical reports, but in vitro simulation to replicate this wear has seldom been attempted and only limited success has been achieved. In the present study, fretting wear was successfully reproduced on the stem surface by incorporating initial stem implantation in a sawbone through bone cement and utilisation of saline solution to mimic in vivo conditions. The stem was examined through optical microscopy, optical interferometry and scanning electron microscopy. In addition, a technique was developed to identify fretting wear based on grey scale threshold, and a grid coordinate system was designed to relocate the position on the stem surface. This study gave scope for comparative investigation concerning the influence of femoral stem design, bone cement brand on generation of fretting wear.*

KEY WORDS: *fretting wear, femoral stem, in vitro simulation, evaluation*

1. Introduction

Total hip replacement (THR) is one of the most common surgical procedures performed in the UK and worldwide, with the aim of improving the quality of life of patients suffering from hip disorders. However, up to 10% of the 60,000 operations carried out each year in the UK are to revise those hip prostheses which have failed prematurely. Nowadays, aseptic loosening has been accepted as the primary reason for failure of cemented THR (Herberts *et al*., 2000), and it can be mainly attributed to wear debris generated by wear of the components (Ingham *et al*., 2000). Recently, great progress has been made in reducing wear at the articulating head–cup interface (Hatton et al., 2002). Consequently, wear at the stem–cement interface is showing an increasing significance in the overall wear of cemented THR (Zhang *et al*., 2008a). The wear debris from this interface can migrate through cement mantle deficiencies to bone tissue areas, where biological process of lytic bone resorption and subsequent aseptic loosening begins (Verdonschot *et al*., 1997).

Since the introduction of cemented THR, the stem–cement interface has been cited as a wear link (Jasty *et al*., 1991) and it is considered to experience fretting wear due to a low-amplitude micromotion under physiological loading. It has been indicated that the stem–cement interfacial strength is critical for initial debonding, which acts as a prerequisite for generation of fretting wear at this interface (Zhang *et al*., 2008 b). However, in spite of the well documented clinical evidence of fretting wear on polished stems, *in vitro* simulation to reproduce this wear has seldom been attempted (Cook 1998). A novel testing methodology has been previously proposed by the present authors to successfully replicate fretting wear on a polished femoral stem through *in vitro* simulation (Brown *et al*., 2007), and this study aims to further evaluate fretting wear by means of optical microscopy, optical interferometry, and scanning electron microscopy.

2. Materials and Methods

2.1. *Preparation of test specimen*

In the present study, a polished Exeter V40^{TM} femoral stem (stainless steel REX 734) and Simplex P bone cement were used. The cement was hand mixed according to the manufacture's instructions, and then transferred into a reamed sawbone in a retrograde fashion employing a cement delivery system. Whilst it is recognised that vacuum mixing is the usual practice, hand mixing was chosen in this case in an attempt to accentuate the deleterious effect of experimental conditions. The stem was implanted, and the cement cured as instructed to mimic surgical techniques. The stem–cement–sawbone system was stabilised using acrulite resin in a steel tube at a position of 10° in adduction and 9° in flexion. A custom-made fixture was designed to enable the *in vitro* simulation employing an Instron test machine.

2.2. *The regime of in vitro wear simulation*

The wear simulation was performed with modification of international standard ISO 7206-4, which specifies endurance test of hip prosthesis. A compressive loading was applied to the femoral head between 0.3kN and 2.3kN in sine wave to represent hip joint force during patient walking (Bergmann *et al*., 1993). The simulation was performed at 3Hz for 5 million cycles, corresponding to about 5 years' *in vivo* wear of the stem (Zahiri et al., 1998). Additionally, 9g/l saline solution was utilised to represent the environmental conditions in the human body. A detailed description of the methodology was available elsewhere (Brown *et al*., 2007), and potential factors such as frequency, creep of bone cement, were also discussed in that study.

2.3. *Analysis of femoral stem following the simulation*

Following the wear simulation, the femoral stem was extracted from the cement mantle and cleaned with Isopropanol fluid. The stem was then evaluated through optical microscopy, optical interferometry, and scanning electron microscopy.

2.3.1. *Optical microscopy*

The femoral stem was visually assessed to establish the overall locations of the worn areas, before the surface morphology was examined employing a Leica optical microscope. A further segregation of the stem was determined using modified Gruen zones, as described by Gruen *et al.* (1979) for review of anteroposterior radiograph of the femoral component, figure 1. A programme was developed to identify the wear damage based on grey scale threshold using Matlab software 6.5. This enabled calculation of coverage of fretting wear in each Gruen zone on the stem surface.

2.3.2. *Optical interferometry*

The femoral stem was measured using a Talysurf CCI interferometer to detect any evidence of surface change. A grid coordinate system was designed to relocate the position on the stem surface, enabling comparison of surface topography pre and post simulation. The efficiency of this relocation system was validated through two measurements performed on the stem surface at different time prior to the wear simulation, figure 2. Quantitative evaluation of fretting wear was carried out with the use of 3D surface parameters—Sq (root mean square deviation of the surface) and Sz (height between the tallest peak and the deepest valley of the surface), and they were calculated using Surfstand software 3.3.

2.3.3. *Scanning electron microscopy*

The femoral stem was cut into small pieces utilising a slitting wheel to facilitate observation of the stem surface with the use of a JEOL JSM-6060 scanning electron microscope. Additionally, the cement mantle was sectioned and then gold-sputtered to enable a scanning electron microscopy.

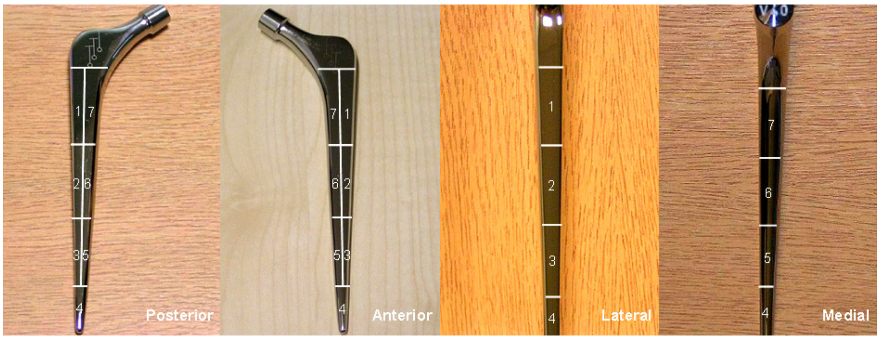


Figure 1. *Definition of modified Gruen zones on the stem surface*

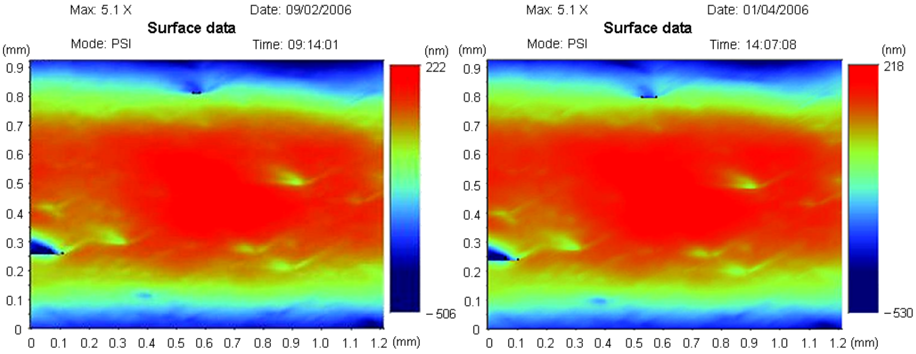


Figure 2. *The grid coordinate system to relocate the position on the stem surface*

3. Results

3.1. *Optical microscopy*

The femoral stem showed typical evidence of worn areas on the surface, which primarily concentrated on anterolateral, posteromedial, and under-neck zones of the stem surface, figure 3. The other areas were smooth and appeared undamaged. No formation of bone cement transfer film was observed. Detection of the wear damage based on the technique developed using grey scale threshold is shown in figure 4, from which it was clear that many undamaged islands were located within the worn areas. These undamaged islands were irregular in shape and surrounded by fretting damage. The coverage of the worn areas in each Gruen zone on the stem surface is shown in table 1, and it was evident that Gruen zone 6 and 7 illustrate the most severe of wear damage.

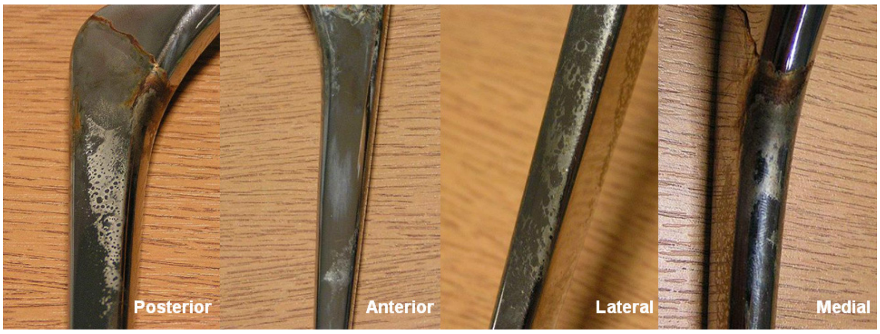


Figure 3. *Reproduction of fretting wear on the stem surface*

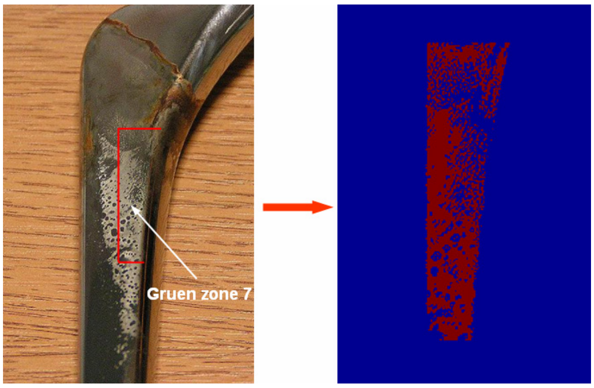


Figure 4. *Detection of worn areas on the stem surface based on grey scale threshold*

3.2. *Optical interferometry*

Figure 5 shows the comparison of the same position on the stem surface utilising the relocation system pre and post simulation. From the figure it was clear that some areas (shown in white square) were severely roughened by the fretting process at the stem–cement interface, whereas the other areas (shown in white ellipse) remained relatively unchanged. Additionally, a total of 20 measurements were performed on Gruen 6 of the posterior surface of the stem, using the Talysurf CCI interferometer. The mean values of the 3D surface parameters Sq and Sz were calculated as 0.42µm and 5.67µm respectively, which showed a significant increase in comparison with the values obtained before simulation (0.04µm and 1.52µm). Figure 6 illustrates one typical measurement, which shows comparison of surface topography between the worn area and the undamaged area. Figure 7 shows the 2D profile of the worn area, from which it was confirmed that the wear damage occurred below the original stem surface. This is considered as one distinctive feature of fretting wear.

Stem surface	Posterior	Anterior	Lateral	Medial
Zone 1	60	0	10	
Zone 2	20	20	90	
Zone 3	0	30	10	
Zone 4	0	0	0	0
Zone 5	10	10		0
Zone 6	80	30		10
Zone 7	90	10		80

Table 1. *Coverage of fretting wear in each Gruen zone on the stem surface*

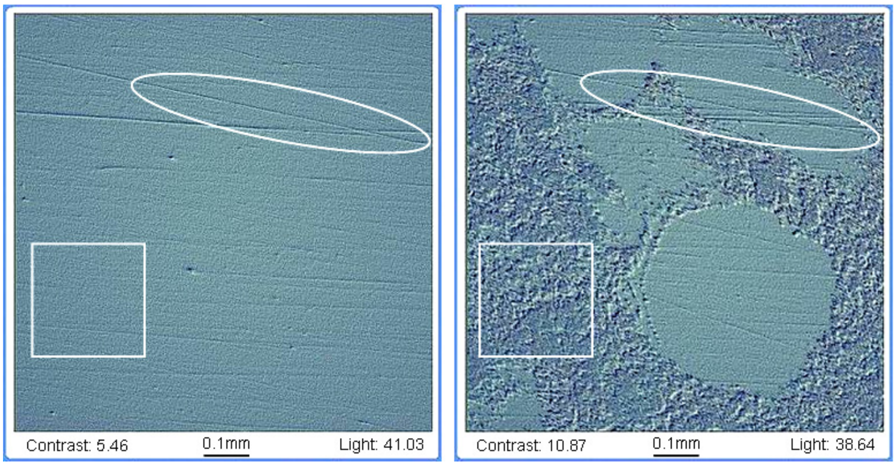


Figure 5. *Comparison of the same measurement position on the stem surface pre and post simulation*

3.3. *Scanning electron microscopy*

The surface topography of the worn areas on the stem surface measured through scanning electron microscopy is displayed in figure 8 (a). The pitting and crater features again confirmed that the wear reproduced on the stem through the *in vitro* simulation was fretting wear. Figure 8 (b) shows the scanning electron micrograph of the bone cement surface, from which it was clear that the cement surface was dominated by many micropores. Additionally, there was an amount of wear debris located in the micropores, which was considered to be liberated from either the stem or the cement surface due to the fretting process at the stem–cement interface. Furthermore, no fatigue cracks were observed across the cement mantle.

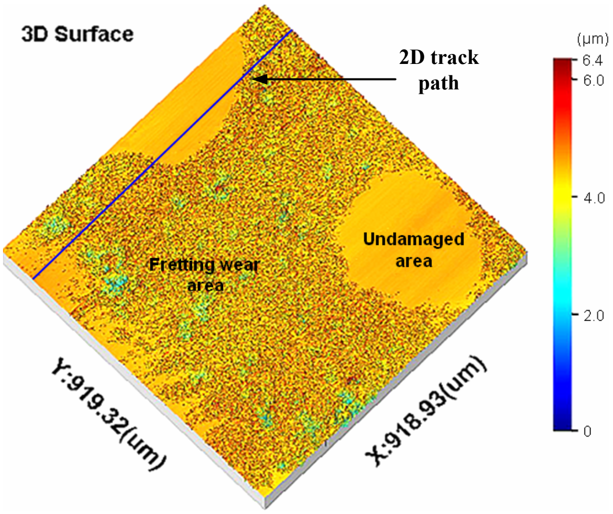


Figure 6. *Comparison of fretting wear area and undamaged area on the stem*

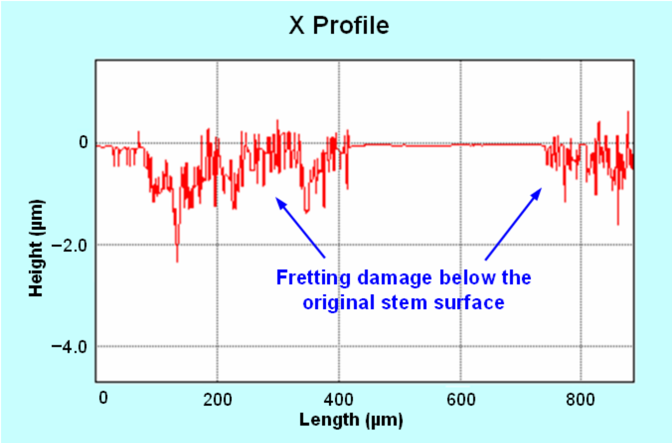
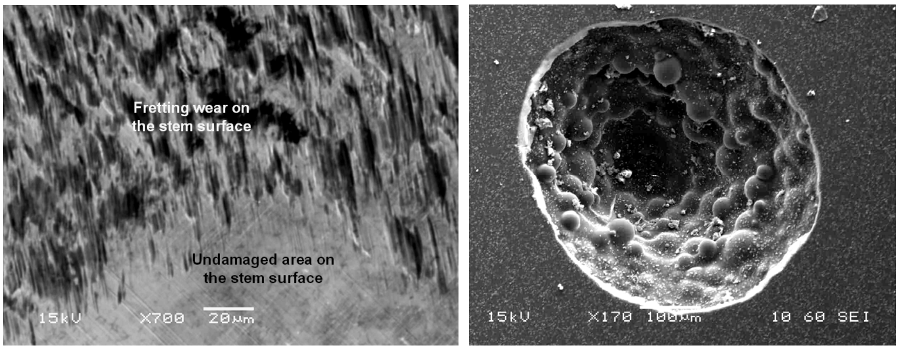


Figure 7. *2D surface profile of the worn areas on the stem surface*



(a) (b)

Figure 8. *Scanning electron micrographs showing (a) fretting wear on the stem surface and (b) wear debris located in the micropores in the cement surface*

4. Discussion

Cemented THR has long been recognised as a situation that can lead itself to wear, which will occur not only at the head–cup interface but also other load bearing surfaces. The stem–cement interface functions as a transitional zone between two materials with significantly different mechanical properties. Fretting wear at this interface has recently been advocated as a potential participant involved in aseptic loosening of the whole joint system. Although fretting wear on polished stems has been clinically reported (Howell *et al*., 2004), limited success has been achieved in reproducing this wear through *in vitro* simulations. Previous pin-on-disk tests using displacement control and static compressive loading cannot represent the *in vivo* environment of the human hip (Ebramzadeh *et al*., 2005). In addition, the potential influence of femoral stem design and bone cement brand on generation of fretting wear has not yet been established. Taken into account the considerable varieties of stem designs and cement brands available on the market (Murray *et al*., 1995; Lewis 2002), an investigation of these contributory factors would clearly be desirable.

A novel *in vitro* testing methodology based on modifications of ISO 7206-4 was proposed by the present authors to reproduce fretting wear and it showed progress in comparison with previous attempts. Fretting wear on the polished Exeter stem was examined through optical microscopy, optical interferometry, and scanning electron microscopy. A technique was developed to identify fretting wear utilising grey scale threshold, and this enabled calculation of coverage of fretting wear on the femoral stem with the assistance of Gruen zones. No bone cement transfer film was detected, although it has been found on the stem surface in previous pull out test to study the stem–cement interfacial strength (Zhang *et al*., 2008 c). It was considered that the transfer film would be removed as wear debris by the cyclical micromotion at the stem–cement interface even if they had been generated in the course of the wear simulation. A relocation system was introduced to compare surface morphology of the same position on the stem pre and post simulation, and quantitative evaluation of fretting wear was enabled using 3D surface parameters, which were considered as a more powerful tool than using traditional 2D parameters. This could be attributed to the insufficient information provided by 2D parameters as they are calculated based on the limited measurement data. Typical features of the worn areas on the stem, i.e. pitting and crater, were evidently shown through the interferometric micrograph and the scanning electron micrograph. They were generated during the fretting process at the stem–cement interface. Additionally, there was no presence of fatigue cracks on the cement mantle, which conflicted to a certain degree with the results of other studies where initiation of micro-cracks was observed at the edge of the micropores (McCormack *et al*., 1996). This could be caused by the relatively limited loading cycles performed in the present simulation, and fatigue cracks may have occurred if the simulation had been continued.

5. Conclusions

Fretting wear was successfully reproduced on polished femoral stems through *in vitro* simulation, and a detailed investigation of fretting wear was conducted using optical microscopy, optical interferometer, and scanning electron microscopy. This study gave scope for further comparative studies of the influence of femoral stem design and bone cement brand on generation of fretting wear.

Acknowledgements

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