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The influence of clearance on friction, lubrication and squeaking in large diameter metal-on-metal hip replacements

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Abstract Large diameter metal-on-metal bearings (MOM) are becoming increasingly popular, addressing the needs of young and more active patients. Clinical data has shown excellent short-to-mid-term results, though incidences of transient squeaking have been noted between implantation and up to 2 years post-operative. Geometric design features, such as clearance, have been significant in influencing the performance of the bearings. Sets of MOM bearings with different clearances were investigated in this study using a hip friction simulator to examine the influence of clearance on friction, lubrication and squeaking. The friction factor was found to be highest in the largest clearance bearings under all test conditions. The incidence of squeaking was also highest in the large clearance bearings, with all bearings in this group squeaking throughout the study. A very low incidence of squeaking was observed in the other two clearance groups. The measured lubricating film was found to be lowest in the large clearance bearings. This study suggests that increasing the bearing clearance results in reduced lubricant film thickness, increased friction and an increased incidence of squeaking.

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1 Introduction

Total hip replacement is a very successful surgical intervention. However, it has long been considered an inadequate solution for the needs of younger, more active patients, due to higher dislocation rates and reduced longevity [1, 2]. Surface replacements were developed to preserve bone stock and increase joint stability, whilst yielding more natural biomechanics. Early designs, employed a metal-on-polyethylene (MOP) bearing failed due to high wear, resultant from the increased sliding distance [3–5]. More recent designs have used a metal-on-metal (MOM) bearing with encouraging short-to-mid-term clinical performance, with high survival rate and swift rehabilitation of patients [6–8]. However, as early generation conventional MOM total hip replacements were often noted to fail due to high frictional torque, concerns exist that the larger bearing may generate torques sufficient to cause frictional loosening.

The material, size and clearance have all been important factors governing the performance of MOM bearings. Many theoretical and experimental studies have determined that MOM bearings in a mixed lubricating regime [9, 10]. Theoretical analysis, using the Hamrock and Dowson equation, suggests that a reduction in clearance would enhance the lubrication of the bearing, and hence reduce friction. In vitro wear studies have shown reduced bedding-in wear with reducing clearance [11].

Clinical cases of transient squeaking in patients with hip resurfacing implants have been noted in recent years, with some reporting an incidence of up to 10% between 6 months and 2 years post-implantation [12]. Back et al. [13] identified 3.9% of their study group (230 patients) had exhibited squeaking, in isolated occurrences within 6 months of implantation. They proposed that the squeaking was due to disrupted fluid film in the bearing.

The aim of this study was to compare the lubrication and friction of surface replacements with three different clearances, whilst noting the incidence of ‘squeaking’ and assessing the sound generated.

2 Materials and methodology

Metal-on-metal surface replacements (ASR, DePuy International, Leeds, UK) with a nominal diameter of 54.6 mm and mean diametric clearances of 94 µm and custom-made replacements with mean diametric clearances of 53 and 194 µm ($n = 4$ for each clearance) were tested with a friction simulator (SimSol, UK). Components were inverted with a flexion-extension of ±25° applied to the head and lubricated with 25% (v/v) and 100% newborn bovine serum. A peak load of 2 kN, with swing phase loads of 25, 100 or 300 N were applied [14]. Tests were performed in a forward and reverse direction, and a mean taken, to eliminate potential errors due to misalignment of the components. The frictional torque generated between the head and cup was measured, and the friction factor was calculated during the high-load, high-velocity phase of the test cycle. Tests were performed for a minimum of 120 cycles.

Sound data was recorded during each friction test using a MP3 recorder and pre-amplifier (Cirrus Research, UK). A microphone was set up at a distance of 50 mm from the implant, and data recorded (where sound was generated) over a minimum of 10 s. Sound data was assessed through narrow band analysis on Frequency Master software (Cirrus Research, UK).

Lubrication was assessed by directly measuring the separation between the head and cup during the test cycle by ultrasonic methods developed at the University of Sheffield (Tribosonics, UK) on one sample of each clearance. A 7 mm diameter piezoelectric sensor was bonded to the back of the cup and ultrasonic reflection measurements were taken during the friction tests at a sampling rate of 100 Hz. Using equations which related reflection coefficient to lubricant properties and film thickness, values for the film thickness were calculated [15].

3 Results

A comparative study examining the influence of clearance on friction, lubrication and squeaking was performed. The set of surface replacements with the largest clearance (194 µm) generated the highest friction factor (Fig. 1), with a mean friction factor of 0.196 (±0.027) in 25% serum. The difference between the largest clearance bearing and the smaller clearance samples was statistically significant in 25% bovine serum, the more clinically relevant lubricant (ANOVA, $p < 0.05$). No statistically significant difference in friction was observed between 53 and 94 µm clearance groups.

The protein concentration of the serum was shown to influence the friction of all three clearance groups, with higher serum concentration giving lower friction (Fig. 2). Tests conducted in 100% serum demonstrated increasing friction with increasing clearance, though there was no statistically significant difference between the mean friction factors of the three clearances (ANOVA, $p > 0.05$).

The peak frictional torques measured in each group, under 100 N swing phase load, 25% lubricant test conditions, are shown in Table 1. The highest frictional torque was measured in the largest clearance (194 µm) bearing.

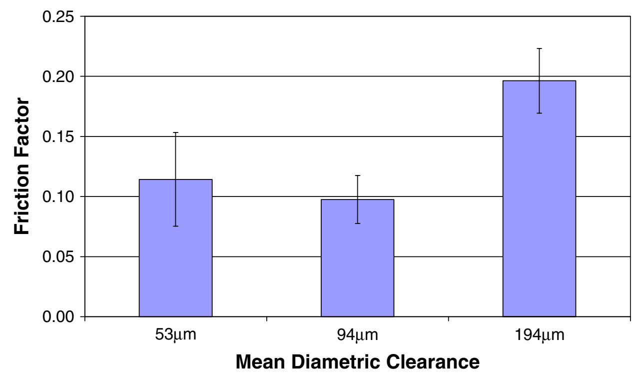

Fig. 1 Influence of clearance on friction (in 25% serum, 100 N swing phase load, 95% confidence limits indicated)

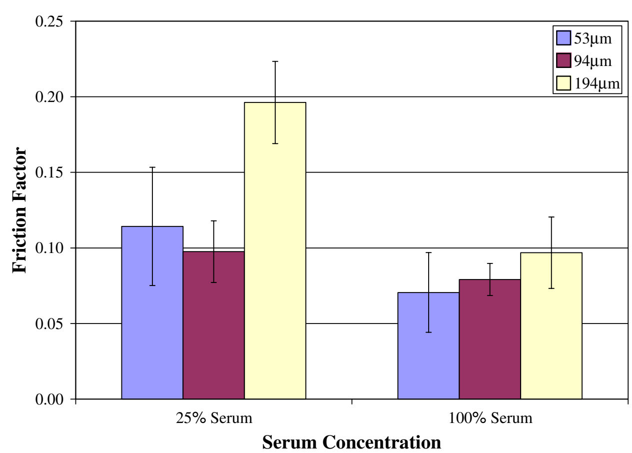

Fig. 2 Influence of serum concentration upon friction (100 N swin phase load, 95% confidence limits indicated)

Table 1 Influence of clearance on peak frictional torque (25% serum, 100 N swing phase load conditions)

Mean diametral clearance/μm	Peak frictional torque/Nm
53	6.55
94	5.33
194	10.51

Sound measurements were recorded from each bearing where squeaking occurred, and the incidence of squeaking under each test condition were noted. 'Squeaking' was observed for all samples in the 194 μm clearance sample group, in 25 and 100% serum. There was a lower incidence of squeaking in the smaller clearance groups (Fig. 3). Analysis of the sounds generated demonstrated a slight negative association between sound frequency and the friction factor.

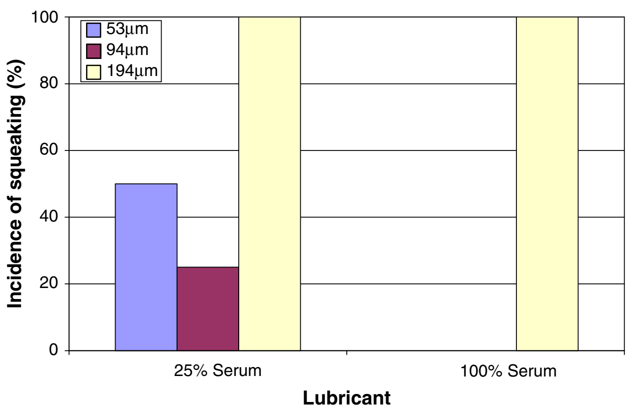

Fig. 3 Incidence of squeaking for each bearing clearance (100 N swing phase load)

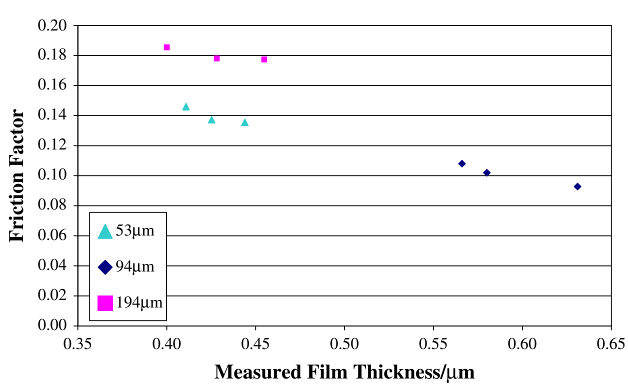

Fig. 4 Influence of diametric clearance upon film thickness (data points for 25, 100 and 300 N swing phase loads)

Ultrasonic measurement of the lubricant film thickness showed the largest clearance bearing to have the thinnest film, and although the 53 μm clearance bearing exhibited similar film thickness. The thickest lubricant layer was measured in the 94 μm bearing, also exhibiting the lowest friction, as shown in Fig. 4. A negative trend of increasing film thickness with decreasing friction factor was observed and for each clearance an increase in friction and decrease in film thickness as the swing phase load increased was also noted.

4 Discussion

This study has examined the influence of diametric bearing clearance on the friction, lubrication and squeaking of large diameter MOM implants through a friction simulator study. Friction studies have often been used to indirectly assess the lubrication of a hip replacement, this study introduces a novel method to directly assess lubrication in the bearing.

The friction study employed a uni-directional flexion-extension motion, and the loading cycle was a simplified model of the gait cycle, with one peak. The bearings are arranged in an inverted position, with respect to in vivo and the cup was not angled.

Diametric clearance was shown to have a significant influence on the friction of MOM bearings. An increase in diametric clearance from 53 or 94 to 194 μm resulted in a significant increase in friction under 25% serum conditions. The small and mid-range clearance bearings had similar friction factors in all test conditions. The friction trends indirectly indicate the smaller clearance bearings have improved lubrication compared with the large clearance bearing. This influence is supported by a number of experimental studies examining the influence of clearance on the wear performance of MOM bearings. In an experimental study of wear, McKellop et al. (1996) saw increasing wear occur as the clearance was increased from approximately 120–390 μm. Several other studies have identified a reduction in diametric clearance as beneficial to the wear performance of a MOM implant [11, 16]. Electrical resistance measurements during a wear study, assessing the separation of the head and cup by lubricant, indicated that a reduction in diametric clearance resulted in longer periods of complete separation of the head and cup during each walking cycle [17].

The effect of clearance on friction was not so apparent during testing in 100% serum, compared with testing in 25% serum. It is proposed that proteins adhere to the surface of the metal bearings, acting as solid phase lubricants to reduce the adhesive forces between the metal–metal contacts. The increased concentration of proteins acting in this role may have partially concealed the effect of the depleting fluid film at the large clearance.

Frictional torque was cited as a reason for failure of early generation bearings, therefore it is still of clinical interest to establish whether the frictional torque generated by a large diameter MOM bearing might be sufficient to cause acetabular loosening. A clinical study by Mai et al. [18] established that frictional torque was not a primary influence in the loosening of large diameter MOM acetabular components, however, no frictional measurements were recorded. Cadaveric assessment of the frictional torque to loosening have been performed by a number of authors [19, 20], examining both cemented and uncemented acetabular cups, however, none appear to have been performed on large diameter MOM bearings. Thus it is difficult to contrast the findings of the present study with the findings of dissimilar cup designs.

The driver for the investigation of the sound generated by MOM bearings was the clinical incidence of squeaking in hip replacement patients, with up to 10% of patients reporting transient squeaking in one study [12]. A recent study examining the in vivo incidence of squeaking in ceramic-on-ceramic bearings noted that cup mal-positioning was often a factor [21]. It suggested that edge loading resulted in a disrupted and compromised lubrication condition, indicating that squeaking may be a lubrication-related phenomenon. The study also highlighted that clinical cases of squeaking were only noted in hard-on-hard bearings. In this experimental study, sounds were recorded during in vitro friction simulator tests, and the incidence of squeaking noted for each bearing combination. The incidence of 'squeaking' was highest in the large clearance bearing group, with squeaking occurring under all lubricant conditions and in most tests. This group also exhibited the highest friction factors, suggesting the bearings were lubricated less effectively than the other bearing groups, potentially causing the squeaking. The findings from the present study suggest that the occurrence of squeaking is related to the lubrication condition of the bearing, in agreement with the conclusions of the study by Walter et al. [21], and the theory presented for the transient squeaking observed in resurfacing bearings [13, 22]. The incidence of squeaking clinically has been noted up to 2 years post-operatively, with no incidence of squeaking reported beyond this. This may indicate that once the bearing has bedded-in, the lubrication condition is improved hence squeaking does not occur. The results achieved within this study appear to suggest there may be a higher incidence of squeaking observed clinically in bearings with larger diametral clearances.

The influence of clearance on lubricating film thickness was directly assessed using a novel ultrasound technique, previously used to successfully examine the film thickness in machine elements [15, 23, 24]. The largest clearance bearings exhibited the thinnest lubricating films, whilst generating the highest friction. However, it must also be noted that the film thickness for the smallest clearance was also reduced, yet this did not have the same impact on the friction. The ultrasound study used only one sample per clearance, and as there appears to be variation between samples in each clearance group for friction, it could be postulated that similar variability could occur in the film thickness. Therefore further test development and more studies may generate a more notable trend.

This study indicated some correlation between friction, lubrication and squeaking. Ultrasonic measurement of lubrication demonstrated reduced film thickness in the large clearance bearing, correlating with increased friction factor. The incidence of squeaking was also greatest in the large clearance bearings, which generated the highest friction. Lubrication theory predicts that an increase in diametric clearance would result in depleted film thickness. An increase of diametric clearance may result in a reduction of film thickness, increasing asperity contact and therefore increasing friction. It is proposed that the depleted lubrication in the large clearance bearings allowed more bearing surface contact, generating the squeaking observed within this study.

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