INTRODUCTION

Metal-on-metal (MoM) hip replacements have re-emerged due to their superior wear properties compared to conventional metal-on-polyethylene (PE) hip joints, and their ability to be used clinically, with large diameters. The MoPE bearings operate in the boundary lubrication regime, whilst the mixed lubrication regime is believed to operate for MoM bearings [1], producing less wear.

Hip simulator studies have shown that MoM bearings undergo a period of initial run-in wear followed by a lower steady state wear. Dowson [2] has reported that geometrical parameters, including bearing diameter and clearance, influence the wear properties during the steady state wear phase. These changes can be attributed to the bearings operating under different lubrication regimes, namely moving from mixed towards full-fluid film lubrication (lambda ratio, $\lambda > 3$) during at least parts of the walking cycle.

Severe gait analyses, such as jogging, have been carried out in recent years showing that highly active patients may exhibit greater wear [3]. The aim of the current study was to investigate whether lubrication theory can accurately predict wear in MoM hip replacements for a range of clearances as well as loading parameters.

MATERIALS AND METHODS

Ten 48 mm diameter MoM hip bearings (high carbon (HC) cobalt chrome molybdenum alloy to ASTM F75), with a range of clearances (two samples of 50, 75, 100 and 150 $\mu$m radial clearances) were supplied by Corin (Cirencester, UK) in the double heat-treated condition (HIPed and solution annealed). Wear tests were performed using an 8-station hip joint simulator (MTS Systems, USA), using a lubricant of 25% newborn calf serum, 17 mg/ml protein content (500 ml). Tests were run up to $3 \times 10^6$ cycles in a reduced load walking condition (1800 N max, 1 Hz) to achieve steady state wear, followed by a period of simulated fast jogging (4500 N max, 1.75 Hz [3]) with 2-hour resting periods every 14,000 cycles, for $0.3 \times 10^6$ cycles, and finally returning to a full load walking test (2450 N, 1 Hz) for $3 \times 10^6$ cycles. Two simulator stations failed during the jogging tests; these bearings were replaced with new components and re-started during the normal walking test, at $4.5 \times 10^6$ cycles and run for $2 \times 10^6$ cycles.

Mean wear rates were determined at various stages of testing as indicated in Figure 1. The ratio of the theoretical $\lambda$, $R_\lambda$, for each activity, was determined and compared to the ratio of the experimental wear rates for the same activities.

RESULTS

The total volumetric wear loss against the number of cycles, for each of the specimens, during all activities is shown in Figure 1. The wear rates, generated from the running-in and the steady state phases, are shown in Table 1.

![Fig 1. Total accumulated wear loss for 50 $\mu$m (triangles), 75$\mu$m (squares), 100 $\mu$m (diamonds) and 150 $\mu$m (circles) radial clearances, during reduced load walking, jogging & normal walking.](image)

According to lubrication theory [1, 2], a smaller clearance would result in a greater film thickness, as shown in Figure 2. Table 2 represents the ratio of mean steady state wear rates (steady state 3 for walking) determined experimentally under different activities for each of the bearing clearances, as well as the ratio of theoretical lambda ratios ($R_\lambda$) for each activity. The $R_\lambda$ was the same for each clearance, under a single activity.

![Fig 2. Theoretical lambda ratio determined for each of the bearing clearances generated under different simulated activities.](image)

**Table 1. Mean wear rates (mm$^3$/10$^6$ cycles) (standard deviation) determined following different activities, for a range of bearing clearances**

<table>
<thead>
<tr>
<th>Clearance ($\mu$m)</th>
<th>Reduced Load Walking</th>
<th>Jogging</th>
<th>Normal Walking</th>
<th>Reduced Load Walking</th>
<th>Jogging</th>
<th>Normal Walking</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>3.94 ± 0.25</td>
<td>2.11 ± 0.04</td>
<td>0.93 ± 0.64</td>
<td>3.58 ± (1.29)</td>
<td>2.11</td>
<td>0.93</td>
</tr>
<tr>
<td>75</td>
<td>5.77 ± 0.32</td>
<td>5.10 ± (0.60)</td>
<td>2.57 ± (0.75)</td>
<td>5.07 ± (0.10)</td>
<td>2.57</td>
<td>0.75</td>
</tr>
<tr>
<td>100</td>
<td>5.07 ± 0.33</td>
<td>7.06 ± (3.16)</td>
<td>0.33 ± 0.76</td>
<td>7.06 ± (3.16)</td>
<td>0.33</td>
<td>0.76</td>
</tr>
<tr>
<td>150</td>
<td>5.71 ± 0.31</td>
<td>6.74 ± (7.11)</td>
<td>1.18 ± 0.75</td>
<td>6.74 ± (7.11)</td>
<td>1.18</td>
<td>0.75</td>
</tr>
</tbody>
</table>

DISCUSSION AND CONCLUSIONS

The theoretical minimum film thickness lubrication is valid for steady state condition where the load and speed are considered to be constant. For the parameters of the current implants, $\lambda$ was found to be <1 for a radial clearance of 150 $\mu$m, indicating that boundary lubrication was likely to be occurring. Smaller clearances have been shown to reduce wear [2], although even at a radial clearance of 50 $\mu$m, full-fluid film lubrication will not be generated. Lubrication theory predicted larger $\lambda$ for smaller clearances which generally supported the experimental results of lower steady state wear rates under smaller clearances.

A higher $R_\lambda$ the ratio of film thicknesses under different activities, should result in a decrease in the experimental wear rate ratio under the same activities; the current results showed that with an increase in the $R_\lambda$, of up to 1.26, for jogging compared to walking, a large increase (over 20 fold), rather than a decrease, in the experimental wear rate actually occurred. Lubrication theory indicated that higher $\lambda$ values would be obtained during the jogging tests with the driving parameter being increased entraining velocity. However, the experimental results showed jogging to produce the highest wear rates amongst all activities, highlighting that the assumptions used in the lubrication theory are not valid under such severe activities. The assumptions used in the lubrication theory are for steady state conditions, which clearly break down under simulated jogging where high loading rates occur.

It may be appropriate for the lubrication theory to be developed to include critical parameters such as loading rates, to enable closer predictions of wear rates, under different loading conditions.

ACKNOWLEDGMENT

This project has been supported by the Medical Devices Faraday Partnership in the form of an EPSRC case studentship (UK). The authors are very grateful to Corin for the supply of all test components and their support of the project.

REFERENCES


**Corin Group, Cirencester, UK**