Effect of Cup Inclination Angle on the Tribology of Metal-on-Metal Hip Bearings

INTRODUCTION:
Metal-on-metal (MoM) hip bearings typically exhibit a short initial period of high wear followed by low steady state wear [1-2]. A recent study has attributed this bi-phasic wear mechanism to the formation of an area of conformance within the wear scar which reduces maximum contact pressures [3]. This study describes a relationship between volumetric wear and a change in the surface geometry of the bearing which in turn leads to lower contact pressures and lower wear rates. High cup inclination angle has been linked to extremely high wear in simulator testing and in-vivo ('run-away wear') [4-5]. This run-away wear phenomenon is not currently well understood and is not explained by traditional elastohydrodynamic lubrication (EHL) theories that are often applied to these bearings [6]. The contact pressure based model may explain this phenomenon.

High inclination angles can result in rim loading of the bearing. As the area of conformance reaches the rim of the acetabular cup, asymmetrical contact occurs which may result in higher contact pressures. These high pressures prevent the bearing from reaching low steady state wear. The hypothesis is that run-away wear will occur if this conformance area reaches the rim of the cup resulting in rim loading (Fig. 1).

METHODS
ProEngineer Wildfire 2.0 was used to generate generic MoM bearings for FEA analysis. Acetabular cup designs used in analysis were similar to commercially available bearings with a 40mm or 56mm internal diameter and a 46mm or 62mm outer diameter. CoCr alloy material properties were used (220GPa modulus and 0.3 Poisson’s ratio). Femoral heads were simplified as a sphere with a small flat for loading with a diameter slightly smaller than its corresponding cup to yield a diametric clearance of 400um. Femoral heads were assumed to be nearly incompressible (220,000 GPa) to allow for perfect conformance with the cup wear scar under loading.

FEA was performed using the Mechanica tool with a half model to reduce analysis time. The total half model contained at least 330 solid elements with up to 9th order edges preferentially located in the contact area. The acetabular cup was oriented at 35°, 50°, and 65° respective to the horizontal with the femoral head oriented vertically. Loading of 1250N (simulating 2450N full model loading) was applied superiorly through the femoral head. This model simulates implantation angles of approximately 45°, 60°, and 75° due to the 10-15° medial orientation of the load path in the hip joint.

To simulate the dynamically changing wear scar on the acetabular cups, spherical sections of various sizes were removed from the superior point of the acetabular cup. The radius of curvature of this section matched the corresponding femoral head. The size of the wear scar was measured as the angular distance from the superior point to the edge of the wear scar and ranged from 15° to 35°. This encompasses the wear area sizes that were found in a 5 million cycle wear study [3].

Wear simulation data for 40mm bearings at 35° was used to correlate wear rates and contact pressures [3]. Contact pressures were then determined for each bearing size, inclination angle, and wear scar size as detailed above. Wear performance was then extrapolated from these contact pressures to determine the ability of each bearing condition to reach low steady state wear.

RESULTS
A linear correlation between contact pressure and wear rate was observed at higher contact pressures (R²=0.84) for the 40mm bearing with 400um clearance. Below a critical contact pressure of 14.5Mpa, a constant low wear rate of less than 2mm/mic was found suggesting that this type of bearing will reach low wear rates after reaching this critical contact pressure.

Fig. 2 shows the contact pressure behavior for 40mm bearings at 35°, 50°, and 65° as well as a 56mm bearing at 65°. At 35° and 50° the 40mm bearing pressure successfully reduced to 14.5Mpa despite some rim contact at 50°. At 65°, extreme rim contact occurred and the 40mm bearing never reached 14.5Mpa. The 56mm bearing successfully reached 14.5Mpa prior to rim contact even at 65°. Fig. 3 compares the contact pressures of the 40mm bearing at 35° and 65° with a large wear area. While the 35° bearing shows a uniform and low contact pressure, the 65° bearing shows non-symmetrical and high contact pressures.

DISCUSSION
The results show that our hypothesis is partially correct in that extreme rim loading can cause high contact pressures while mild rim loading may still result in good wear performance. Bearing size and clearance also had an effect on this process. With all other features constant, increased bearing diameter was shown to be more tolerant of higher inclination angles. This is due to the increase in available surface for the conformance area to form prior to reaching the rim. Even at 65° a 56mm bearing was found to reach the critical contact pressure (Fig. 2).

This study has shown a correlation between contact pressure and wear rate for MoM bearings. The contact pressure was shown to dramatically decrease with the formation of a conformance area which results in a reduction of wear. High cup inclination angle was shown to cause rim loading which may lead to high contact pressures and therefore high wear. This corresponds to clinical and simulator studies showing high inclination angles causing extremely high wear rates. Furthermore, this study has demonstrated the effect of bearing diameter on this contact pressure model. These results suggest that while implantation angle is the primary factor in MoM wear rates and is dictated by surgical procedure, certain design parameters may be engineered using this contact pressure model to reduce the risk of run-away wear and produce a more clinically forgiving bearing.

REFERENCES