Comparative Wear Performance of Ceramic-on-Ceramic Bearings under Non-Standard Hip Simulation

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INTRODUCTION: The articulation performance of candidate bearings for total hip arthroplasty (THA) is typically evaluated *in vitro* using standard orbital hip simulators. For expediency purposes, these tests are usually performed in continuous motion for in excess of 5 million cycles (Mc). However, human gait kinematics differs markedly from simulation, and includes non-orbital motion interspersed with numerous stop-rest-start sequences. The purpose of this study was to examine the effect of non-continuous motion (*i.e.*, stop-dwell-start) on the wear behavior of two self-mated ceramic-on-ceramic (CoC) bearing couples, silicon nitride (Si_3N_4) and alumina (Al_2O_3). The null hypothesis was that there would be no differences in wear between the two bearing couples regardless of hip simulator conditions.

METHODS: Six Ø28 mm and three Ø40 mm matched Si_3N_4 head and liner pairs (*MC*[2®], Amedica Corporation, Salt Lake City, UT, USA) with three similar Ø28 mm Al_2O_3 (BIOLOX® *forte*, CeramTec, Plochingen, Germany) pairs were tested in a 12-station Shore-Western hip simulator (Shore-Western, Monrovia, CA, USA). All bearing pairs were mounted anatomically with a 30° cup angle. The lubricant was alpha-calf serum (HyClone, Logan, UT USA), diluted with DI water to obtain a protein concentration of 20 mg/ml and pH of 8.0. EDTA was added (20 ml per L) to reduce calcium film in accordance with previous studies.[1] Lubricant change-outs occurred every 0.5 Mc. Other test parameters were representative of ISO 14242. Gravimetric wear results obtained at 0.25, 0.5, 1, 1.5, 2 and 3 Mc were converted to volumetric wear using density values of 3.27 g/cc and 3.98 g/cc for Si_3N_4 and Al_2O_3, respectively. Surface roughness, scratches, and protein deposition profiles were evaluated using a non-contact surface analyzer (New View 5000, Zygo, Middlefield, CT). The standard ISO 14242 continuous Paul orbital duty cycle test sequence was interrupted at 3.0 Mc due to near zero wear. It was altered for the next 2.0 Mc to include a 35 second dwell at maximum load, (*cf.* Figure 1). It was envisaged that a dwell at constant load would likely expel serum lubricant from the contact zone between head and liner pairs requiring subsequent acceleration to overcome unlubricated static friction, with the combined effect of adverse wear for these hard-on-hard bearings.

RESULTS: Head, liner and combined volumetric wear rates for this CoC hip simulator study at 3.0 Mc are provided in Figure 2. For Ø28 mm couples, there were no significant differences in wear rates between Si_3N_4 and Al_2O_3 bearings, with both essentially showing near zero wear. In fact, within experimental error, the Ø28 mmSi_3N_4 femoral heads had a slight weight gain whereas their corresponding liners indicated an opposite trend. As expected, there was more wear with Ø40 mm Si_3N_4 couples than either the Ø28 mm Si_3N_4 or Al_2O_3 bearings, leading to significant differences in head ($p = 0.02$) and combined ($p = 0.05$) wear rates, but, interestingly, no differences in liner wear rates. The Ø40 mm Si_3N_4 heads and liners showed continual, but minimal material loss throughout the 3.0 Mc test. There were no Ø40 mm Al_2O_3 controls included in this simulator study. The wear performance of CoC Si_3N_4 and Al_2O_3 bearings up to 3.0 Mc are comparable to other hard-on-hard bearings and both are superior to CoCr-on-CoCr bearings. Conversely, also presented in Figure 1 are combined average wear rates for all bearing materials and sizes after introduction of the *stop-dwell-start* loading sequence at 3.0 Mc. This had a significant effect on CoC wear performance, particularly for the Si_3N_4 couples. The combined average for both Ø28 mm and Ø40 mm Si_3N_4 bearing pairs increased to 2.93 mm^3/Mc, while the Al_2O_3 controls showed increased variability, but remained near zero wear. In particular, an abrupt loss of material was noted for two of the six Si_3N_4 bearings between 3.0 Mc and 5.0 Mc, (one each of Ø28 mm and Ø40 mm), whereas the remaining four Si_3N_4 couples had essentially zero wear, comparable to the Al_2O_3 couples.

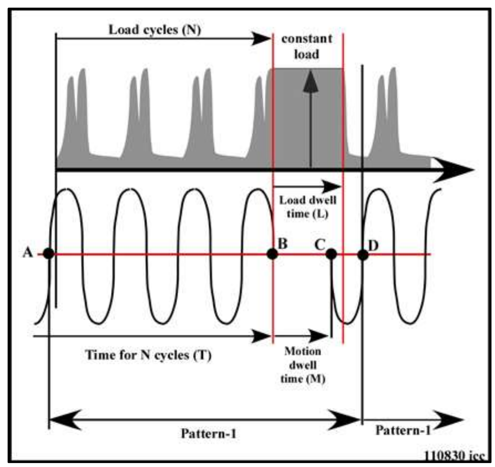

Figure 1. Modification of load and cycle profile for CoC wear study.

DISCUSSION: The contrasting use of the non-standard cycle, which included the hold sequence at maximum load, played a significant role in lubrication breakdown and increased friction, particularly for the Si_3N_4 self-mated bearings. The *stop-dwell* segment likely expressed lubricant out of the contact area between the head and liner leading to a breakdown of fluid film and resumption of boundary layer lubrication. Contacting asperities between surfaces then dramatically increased static friction, leading to their microfracture upon re-*start* of the bearing. Scuffing and microfracture were observed on the high-wear Si_3N_4 bearings. Thermally activated dissolution of the bearing surface (or wear debris) and reformation of the tribochemical film ensued which lowered friction, until the bearing once again came to its next *stop* in the cycle, resulting in a repetition of *stick-slip* behavior.

SIGNIFICANCE: While the standard Paul cycle is used for test expediency, continuous motion simulation does not adequately represent actual human gait.[2] Alternatively, a *stop-dwell-start* protocol is more clinically relevant, and may more effectively discriminate between bearing materials.

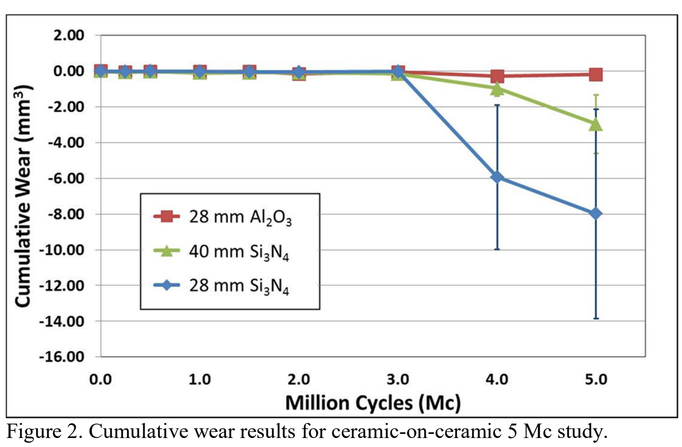

Figure 2. Cumulative wear results for ceramic-on-ceramic 5 Mc study.

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