Hertzian Contact Theory Applied to Edge-Loaded Ceramic-on-Ceramic Hip Bearings: Analysis and Validation

INTRODUCTION: This work addresses the problem of wear of ceramic-on-ceramic bearing couples used in total hip arthroplasty. A wear pattern called stripe wear has been observed on retrieved ceramic femoral heads. It typically appears as a long, narrow, roughened area on affected implants. Evaluation of the wear stripe has revealed grain removal and material loss to depths of 30 μm [1]. It has been theorized that such damage is caused by contact between the femoral head and the edge of the acetabular cup. An edge-loaded contact is much less congruent than normal contact, and it would cause increased contact stress, leading to the wear stripe. Edge-loading may be due to small separations of the head from the cup, as observed radiographically [2]. Simulator wear tests involving such separation have yielded wear stripes similar to those on retrieved bearings [3].

The hypothesis of this work is that the contact mechanics of edge-loaded hip bearings can be accurately described using Hertzian contact theory. When applicable, the Hertz theory can be used to accurately model contact dimensions, normal pressures, and stress fields. The Hertzian theory has previously been used to describe the contact mechanics of the congruent hip couple [4], but not the edge-loaded couple. If determined to be applicable to edge-loaded bearings, the Hertz theory would offer the benefit of an analytical solution to a complicated problem. Simplified computation of edge-loaded contact stresses could benefit wear modeling and testing of ceramic-on-ceramic bearings.

METHODS: The edge-loading scenario was modeled as shown in Fig. 1. Normal contact between the femoral head and the radius of the cup occurs at A, where the tangent to the edge is horizontal. The geometrical model for the Hertzian contact analysis is depicted in Fig. 1. For the Hertzian contact analysis the head surface was taken to be a sphere, as described in [1]; no such segment was modeled in this work. Multiple potential contact points, the center B of the edge radius was taken as a fixed pivot, and the cup inclination θ was varied. For each angle θ, an associated distance δ, representing the head-cup separation, was computed. For loading, the cup was considered fixed, and load was applied vertically through the center of the head.

A validation experiment duplicating the scheme of Fig. 1, the femoral head was mounted to the vertical rod of an axial test machine. The cup was first assembled rigidly into a hemispherical hole in an oversize block of rigid polyurethane foam (30 p.c.f., ASTM F-1839). A variable angle sine plate, fixed for the desired angle, was placed in the test frame, and the cup and block were positioned on the surface of the sine plate in a manner to establish normal contact at the desired point A. To record the contact patch, first, the edge of the cup was coated with toner powder revealed the contact patch where the powder stuck to the transferred grease. The contact patch was measured and digitized at 145X magnification using a video coordinate measuring machine (Nikon Nexiv VMR 3020).

RESULTS: A 36 mm coupled was examined at three different positions and under loads from 200-1400 N. Figure 2a shows a photo of the contact patch after 1000 N at θ=20° (δ=4.7mm). Figure 2b shows superimposed images of the computed and the measured contact patches for two other trials. Here, the measured results are the 2D projections of the 3D contact patch on the head. The major axis was taken simply as the tip-to-tip length of the projected contact patch.

DISCUSSION: The measured contact patch length was similar to the value predicted using Hertz’s theory. The same was true for the width at the greater separations, but the measured width was >2.0 the predicted width at the 15° position (Fig. 2). Also at 15°, the measured length differed most from the prediction. These discrepancies may be due to a short conical segment located between the edge radius and the concave sphere, as described in [1]; no such segment was modeled in this work. Generally, at lower loads and greater separations, the contact patch tended towards the true elliptical contact of the theory. For higher separations, the Hertz theory closely predicts the contact mechanics, but further work is needed to evaluate the component geometry and the predictions for lower separations.

The smaller separation values (3.0, 4.7 mm) were in the range reported in a radiographic study [2]. The peak computed pressures were high compared to the peak compressive stress (62 MPa) reported for congruent contact [4]. Physiologically relevant edge-loading may cause contact stresses that approach or exceed the material strength; nonetheless, scale effects and the entire stress tensor should be considered in any wear or failure model applied to this loading scenario.