Quantifying Deformation and Recovery of Polyethylene in Total Knee Replacement

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Statement of Purpose: Total knee replacement (TKR) is increasingly popular. By the year 2030 an estimated 3.5M TKR's could be implanted in the U.S. alone [1]. Premature failure of TKR due to wear and other factors can produce pain and distress for the patient, necessitating costly revision surgery [2]. To elucidate wear mechanisms and improve the longevity of future designs, researchers investigate wear in clinical and laboratory settings. While gravimetric methods (ie weighing) are the gold standard for laboratory investigation, volumetric methods can identify the location of wear and connect to clinical studies. Unfortunately, volumetric methods confound influences of wear and deformation. As a first step in decoupling wear and deformation, this experiment focuses on methods for quantifying deformation and resulting recovery of a simplified TKR articulation.

Methods: A knee simulator (AMTI, Watertown, MA) was used to create a simple water lubricated articulation of a Sigma femoral component (DePuy, Warsaw, IN) against a Sigma fixed bearing polyethylene insert (DePuy) that was machined flat to a thickness of 8mm. The input motion consisted of a constant vertical load (0.25, 0.5, 0.9, 1.8, and 3.6 kN), sinusoidal flexion (0° to 30°) about the distal sagittal femoral radius, with no internal-external rotation, no anterior-posterior motion, and no anterior-posterior tilt. Varus-valgus motion was fixed, while medial-lateral motion was unconstrained. Prior to each load condition, the proximal surface of the insert was coated with blue toolmakers ink to characterize the contact scar. After each 1000 cycle loading interval, various methods were used to quantify the resulting deformation as well as the area of contact. Specifically the depth of penetration (ie maximum deviation from an idealized best fit of the proximal surface) was measured using a contact profilometer (Zeiss Surfcom 5000, Maple Grove, MN) and a 3-D laser scanner (Metron G2-24, Snoqualmie, WA) with post processing performed in Geomagic Qualify (Research Triangle Park, NC). Deformation recovery was also determined 1 and 2 days after the 3.6 kN interval. Contact area was qualitatively assessed through photographs showing the removal of toolmakers ink from the insert as well as images of the deformed inserts generated from the laser scans. These qualitative images of contact area were then quantified using Image-J (NIH, Bethesda, MD). Deformation and contact area were also estimated using linear elastic Hertzian contact theory [3]. Wear was not quantified.

Results: In general agreement with theory, deformation and contact area increased with increasing applied load, and then partially recovered after 1 and 2 days (Figure 1). Somewhat surprisingly, the contact scars were different beneath the medial and lateral condyles, indicating imbalanced loading (Figure 2). The lateral scars were larger and consequently easier to detect at low applied loads (eg Figure 2), therefore results are only presented for the lateral scar. While the maximum deformation methods appear to match theory, the measured contact areas are much larger than theory.

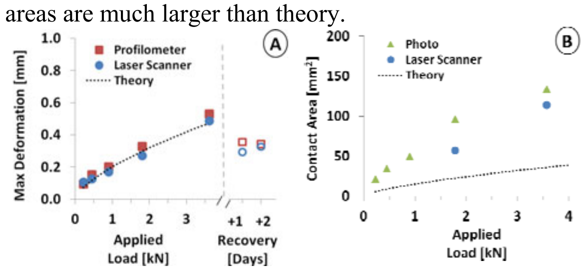

Figure 1. Maximum deformation (A) and contact area (B) of the lateral scar using profilometer (square), photos (triangle), laser scans (circle), and theory (dotted line). Note inserts were analyzed after removal from the knee simulator.

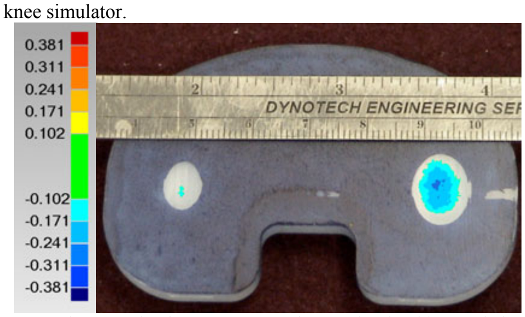

Figure 2. Photograph of contact scars after 1.8 kN load interval showing blue tooling ink removed during articulation. The laser scanner image from the same interval is superimposed, units in mm.

Conclusions: Polyethylene exhibited large deformations under these loading conditions, demonstrating the need to account for deformation if volumetric analysis is used to quantify wear. Also deformation recovery should also be considered, allowing ample time to achieve steady state. Linear elastic theory may not be valid in this range of loading as evidenced by the disagreement with contact area results (Figure 1) as well as estimated stresses (30+ MPa) that exceed yield even at relatively low applied loads. Contact profilometry and laser scanning methods showed good agreement with each other, especially for maximum deformation. Their agreement with theory is misleading, because the measurements were taken 5-15 minutes after the load was removed and likely under-predict the loaded deformation. Investigators using volumetric wear methods and radiostereographic analysis should take care to understand the contribution of deformation and specifically the viscoelastic and plastic behavior of polyethylene in Hertzian contact.

References: [1] Kurtz, et al, JBJS, 2007. [2] Ong, et al, CORR, 2006. [3] Young and Budynas. *Roark's formulas for stress and strain*, 2002.

Abstract #803