INTRODUCTION: Various techniques have been developed to evaluate the femoral head penetration into acetabular polyethylene (PE) liners that occurs due to articular wear and creep deformation after total hip replacement (THR). Clinically, 2-dimensional (2D) or 3-dimensional (3D) in-vivo radiographs are used to measure this penetration.\(^\text{1-3}\) In vitro laboratory techniques applied to retrieved worn PE liners utilize coordinate measuring machines or shadowgraphs of polymer casts to measure this penetration depth.\(^\text{2,3,5}\)

Previously, we reported a simple, direct measurement technique to analyze the 3D head penetration depth in retrieved acetabular PE liners.\(^\text{6}\) The objective of this study is to compare this direct 3D measurement technique with other in vitro techniques for measuring head penetration depth into retrieved PE liners.

METHODS: Fifteen modular acetabular PE liners with a 28-mm or 32-mm femoral head retrieved after a mean of 12±6 years (range, 1.6-19.6) of in-vivo function. Patient age and weight at retrieval averaged 62±12 years and 72±16 kg, respectively. Retrieval reasons were PE wear (5), loosening (4), infection (1), post-mortem (1), cement fracture (1), and unknown (3).

Femoral head penetration depth was measured using the three different techniques detailed below. The PE liners were examined to determine the plane of maximum wear and all 2D measurements were made parallel to this plane. The penetration angle associated with maximum wear was calculated relative to the face of each liner. All measurements were performed 5 times per PE liner, and penetration depth and penetration angle were averaged. Absolute differences between techniques were calculated for each PE liner and averaged.

3D Direct measurement: The retrieved liners were measured using a digital stylus (Microscribe 3DX, Immersion Corp, CA) with a femoral head attached to the stylus tip. The 3D penetration depth into the PE liner was calculated as the vector length between the head center positioned in two distinct contours, consistent with the unworn and worn articular regions (Fig.1a) using custom software.\(^\text{6}\)

Cast measurement: All retrieved PE liners were cast using silicone (OOMO\(^\text{TM}\)25, Smooth-On Inc, PA, Shrinkage <0.25%). Surface profiles of the unworn and worn regions on the casts were measured using a digital stylus (Microscribe 3DX) with Rhinoceros software (McNeel, WA). The 2D penetration depth was calculated as the length between the centers of digital circle templates fitted to the unworn and worn regions (Fig.1b).

Radiographic measurement: Digital radiographs were taken with the femoral head positioned in the unworn and worn regions, respectively (Fig.1c). The femoral head center was determined in each radiograph and the 2D penetration depth was calculated as the length between the head centers using image analysis software (Image J, NIH, MD).

RESULTS: The three measurement techniques had significant linear relationships \((p<0.001)\) with regression coefficients exceeding 0.88 (Fig. 2), and were significantly correlated (Spearman Correlation, \(p<0.001)\). However, penetration depth measured for each liner using the cast technique was significantly different from the 3D direct (paired t-test, \(p<0.001)\) and radiographic (paired t-test, \(p<0.001)\) techniques. The magnitude of head penetration for the 3D direct and radiographic techniques was not significantly different (paired t-test, \(p=0.216)\). Penetration depth derived from cast measurements were generally larger than the values derived from both 3D direct and radiographic measurements. Differences in the penetration depth for the 3D direct and radiographic measurements were 85µm, 150µm, and 115µm, respectively.

DISCUSSION: Estimates of femoral head penetration can be accurately acquired from retrieved PE liners. The 3D direct technique provided a measurement of penetration depth comparable to the radiographic technique that is routinely applied to clinical radiographs. In contrast, the cast technique significantly overestimated the penetration depth, likely due to errors in digitizing multiple points to define the contour shape of the silicone casts. It is recommended that more accurate shadowgraph techniques\(^\text{6}\) be used for measuring casts. This novel technique allows a direct measurement of 3D femoral head penetration into PE liners by identifying head displacement between the unworn and worn regions. In clinical radiographs, 2D measurements are generally considered to underestimate the true liner penetration due to the multiple wear vectors occurring in vivo.\(^\text{5}\) Identifying the plane of maximum wear for all PE liners provided penetration measurements that more closely approximated the 3D wear.

Average penetration angles ranged from 20°-26°, with wide variation between the liners that is consistent with variations that can occur in surgical alignment of the acetabular cups during in vivo function.