Introduction
Debates currently surround the mechanical and fatigue properties of highly cross-linked polyethylene in TKA, thus requiring advanced study of components [1]. No current technique allows for delamination and subsurface cracking to be studied in a highly accurate, non-destructive and quantitative manner. Visual inspection and microscopy does not detect the smallest regions of delamination, specifically the initial subsurface cracking [2]. Scanning electron microscopy (SEM) is destructive to the specimen and may destroy some of the smallest cracks [3]. Ultrasonic techniques provide only low-resolution images and limited quantitative information regarding the subsurface cracks, with no information on surface damage, limiting its practical application [3]. An accurate, non-destructive method to quantify both surface wear and subsurface changes in polyethylene components would be highly advantageous for retrieval and simulator studies. We report the development of such a technique to quantify subsurface cracks using micro-computed tomography (micro-CT), extending its previously reported use for measuring surface and volume changes due to wear.

Methods
Three severely delaminated inserts were obtained from our institution’s implant retrieval library for the study. Inserts with obvious, extensive delamination were selected, as these would be the most likely to have subsurface cracking. Two never-implanted inserts, that would not be expected to have any deviations in their subsurface structure, were also obtained. The three delaminated inserts included one AMK (DePuy Inc., Warsaw, IN), one Kinemax, and one Duracon (Stryker Inc., Kalamazoo, MI). The lengths of implantation were 15 years for the AMK and Kinemax, and 11 years for the Duracon. All had obvious delamination across the articular surfaces. The new, never implanted inserts included one AMK and one Genesis II (Smith & Nephew, Memphis, TN).

Each insert was scanned with a micro-CT scanner (eXplore Vision 120, GE Healthcare, London, ON) in a previously described fashion [4-5]. All scans were obtained using an isotropic resolution of 50 μm. The reconstructed scan images were analyzed with dedicated micro-CT software (MicroView v2.2, GE Healthcare, London, ON). A threshold was determined automatically for each reconstructed scan by the software. Windowing was adjusted to aid visualization. For each insert, projections were visualized for each slice in the X, Y, and Z planes. The presence of subsurface cracks and their location was noted, and screen captures were obtained. For a subset of slices where cracks were present, the digital line tool within the software was used to measure the minimum and maximum crack widths, as well as distance from the articular or backside surface. A region of interest (ROI) was selected beneath one side of the articular surface of the Kinemax insert, and a region-growing tool was used to select the majority of the subsurface cracks within the ROI. Isosurface rendering was performed to create a three-dimensional volume of the subsurface cracks within the ROI, and of the entire insert surface. The resulting volumes were visualized in ParaView (KitWare Inc., Clifton Park, NY).

Results
Subsurface cracks were readily apparent in the two-dimensional planar images of the delaminated inserts (Figure 1A-D). The cracks predominantly ran horizontally, just below the articular surface of the inserts. The cracks tended to expand from narrow openings to larger gaps, running from just below the surface to further down within the surface. Vertical cracks were also found at the centre of one insert and at the lateral edge of the articular surface. In one case, a horizontal crack was seen just below the backside surface of the insert. Unlike the cracks below the articular surface, there were no obvious surface changes that suggested the presence of the crack below the backside surface. In some cases, small regions of greater x-ray attenuation (i.e. denser material) appeared at the outermost edges of the cracks. The subsurface of the never-implanted inserts was uniform and devoid of cracks.

The location (measured as depth from surface) and width of the cracks were easily determined using the viewing software’s linear measurement tool. For cracks beneath the articular surface, depths ranged from 0.12 mm to 6.01 mm, with crack widths ranging from 0.06 mm to 0.97 mm. The crack above the backside surface was 0.23 to 0.44 mm in width and was 0.26 to 1.95 mm from the backside surface. The three-dimensional rendering of the cracks within one region of the insert demonstrated the extensive nature of the cracks (Figure 1E).

Discussion
Micro-CT was successfully used to non-destructively visualize and quantify subsurface cracks due to delamination in retrieved tibial inserts. The extent of this subsurface cracking was not apparent from examining the insert surface. Interestingly, denser regions appeared at the edges of some of the cracks, signifying that the polyethylene was compressed at these locations. This could be a sign of the initial formation of the cracks, suggesting micro-CT might be able to track the propagation of the subsurface cracking over time. As micro-CT is non-destructive, additional tests may be performed on the components after scanning, or allow the components to be scanned at multiple time points such as in a pin-on-disk or wear simulator study. Other measurement techniques cannot directly visualize the cracks, or are destructive, or do not also quantify surface deviation in addition to the subsurface cracking [2-3].

Micro-CT is suitable for evaluating all types of polyethylene used in joint replacement, including hip, knee, and spinal arthroplasty [4-5]. The new use for micro-CT described here expands the completeness of the technique, enabling quantification of both surface and subsurface damage in all types of polyethylene-based arthroplasty components from in vitro and ex vivo sources.

References