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Surface extraction can provide a reference for micro-CT analysis of retrieved total knee implants

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Background: Quantitative measurements of damage and wear in orthopaedic components retrieved from patients during revision surgery can provide valuable information. However, to perform these measurements there needs to be an estimate of the original, unworn geometry of the component, often requiring multiple scans of the various sizes of components that have been retrieved. The objective of this study was to determine whether the articular and backside surfaces could be independently segmented from a micro-CT reconstruction of a tibial insert, such that a tibial insert of one thickness could be used as a reference for a tibial insert of a different thickness.

Methods: New tibial inserts of a single width but with six different thicknesses were obtained and scanned with micro-CT. An automated method was developed to computationally segment the articular and backside surfaces of the components. Variability between intact and extracted components was determined.

Results: The deviations between the comparisons of the extracted surfaces (range, 0.0004 to 0.010 mm) were less ($p < 0.001$) than the baseline deviation between the intact surfaces (range, 0.0002 to 0.053 mm).

Conclusions: An extracted surface from one insert thickness could be used to accurately represent the surface of an insert of a different thickness. This greatly enhances the feasibility of performing retrieval studies using micro-CT as a quantitative tool, by reducing the costs and time associated with acquiring, scanning, and reconstructing multiple reference tibial insert geometries.

Clinical relevance: This will add greater detail to studies of retrieved implants, to better establish how implants are functioning in vivo.

1. Introduction

Components retrieved during revision surgery for a failed total joint replacement have long been a valuable source to assess the in vivo function of joint replacement implants [1,2]. Traditional semi-quantitative damage scoring techniques have been joined by three-dimensional quantitative measurements, such as micro-computed tomography (micro-CT), in order to accurately assess damage due to wear and creep on the implant's bearing surface, typically made of polyethylene [3,4]. In order to make these quantitative wear measurements with micro-CT, an unworn reference component must be available [3–5]. In most cases, this will be a separate component from the one that was implanted in the patient, as the component is unlikely to have been scanned before it was implanted in the patient.

The use of a different component for a reference than the one that was implanted raises the issue of manufacturing tolerances. Variability between polyethylene tibial inserts from total knee replacement has been examined before, with differences found to be up to 0.21 mm [5]. In some cases this may be great enough in magnitude to affect the measurements of wear in retrieved inserts (including with micro-CT), especially those with short implantation times [5–7]. To minimize the effect of this manufacturing variability, it has been suggested that multiple reference components should be obtained and their geometry averaged together [7]. However, the modularity of the total joint replacements makes this challenging, as for a single model of total knee replacement, the polyethylene tibial inserts may come in a half dozen diameters and a further half dozen thicknesses. The feasibility of obtaining, scanning, and averaging multiple tibial inserts for each diameter and thickness available is low [8], even if it would produce more accurate results. Methods to estimate the original geometry of the retrieved tibial insert from unworn regions of the same insert have been developed [8] and may be even more accurate than using a separate reference component, but this has not been implemented with micro-CT. These methods typically rely on point cloud data and line fitting techniques, which are well suited to the data acquired with coordinate measuring machines (CMM) but would require significantly

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more post-processing to accomplish with micro-CT, in which surface geometries are generated by converting an image volume directly to a triangulated surface mesh.

Two of the most important aspects of a retrieved tibial insert to be studied are the articular (top) surface, which forms the bearing surface against the femoral component counterface, and the backside (bottom) surface, that locks into the tibial baseplate [2,9]. While the overall thickness of a tibial insert may change, for a given diameter the profile of the articular and backside surfaces stays the same, to be consistent with the articulating femoral and tibial components. Therefore, if it were possible to examine these surfaces in isolation from the remainder of the tibial insert, there would no longer be the requirement to have multiple reference tibial inserts of different thicknesses. The objective of this study was to determine whether the articular and backside surfaces could be independently segmented from a micro-CT reconstruction of a tibial insert, and using this method, whether a tibial insert of one thickness could be used as a reference for a tibial insert of a different thickness. We hypothesized that the variability between the extracted tibial insert surfaces from two different thicknesses would be equivalent to the variability between the intact geometries of different tibial inserts that were of the same thickness.

2. Methods

2.1. Tibial inserts and micro-CT scanning

Eighteen new, never implanted polyethylene tibial inserts of a single model (Genesis II, Smith & Nephew, Memphis, TN, USA) were obtained. The inserts were made from conventional, non-crosslinked polyethylene using GUR 1050 resin, and were sterilized with ethylene oxide (EtO). All were posterior-stabilized, size 3/4, and included three specimens in each of the six difference thicknesses: 9 mm, 11 mm, 13 mm, 15 mm, 18 mm, and 21 mm (Fig. 1). Each insert was scanned with a laboratory micro-CT scanner (Vision 120, GE Healthcare, London, ON, Canada), with an X-ray tube voltage of 90 kVp and a current of 40 mA [6]. There were 1200 views per scan in 0.3° increments, at 16 ms exposures, with 10 frames averaged per view to reduce noise. The isotropic voxel spacing was 50 μm. Each scan volume was reconstructed at the full resolution, and isosurface rendering was used to generate the three-dimensional surface of the scanned tibial insert geometry, in STL format, from the reconstructed volume. The largest STL file was the 21 mm thick insert, and had a file size of 1.9 GB (STL ASCII format).

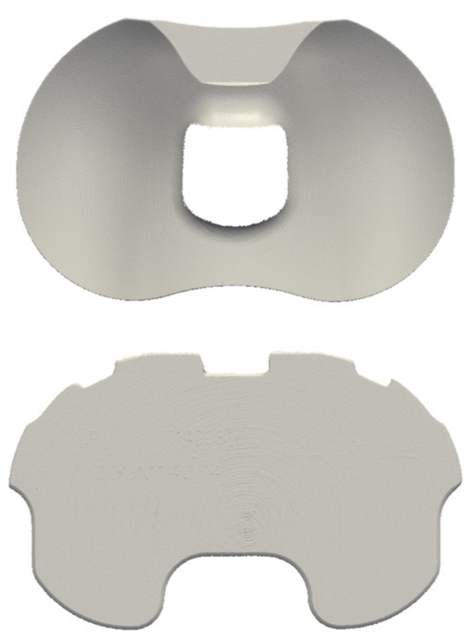

Fig. 1. The extracted articular (top) and backside (bottom) surfaces from the 9 mm thick intact tibial insert.

2.2. Baseline variation between intact tibial inserts

A previously validated software utility was used to co-register, average, and plot the deviations for each trio of tibial inserts of the six thicknesses [7]. The software registers two geometries together at a time using an iterative closest point algorithm. This is performed automatically, using 1000 test points across the entire geometry. Convergence was set for when the root mean square distance between the test points dropped below 0.1 μm. Once registered, the three-dimensional deviations between the two geometries are measured across the entire surface, and plotted as a deviation map. The surfaces of the geometries are then averaged together. These steps serve two purposes: First, to establish the baseline variation (due to manufacturing tolerances) between different tibial inserts of the same thickness, independent of the surface extraction process; second, to generate averaged surfaces where this manufacturing variability would be diminished for use in the surface extraction, so that the major variability in the extracted surfaces would be due to the extraction itself and any differences in the surfaces of tibial inserts of different thicknesses.

2.3. Articular and backside surface extraction

A custom software utility was first used to appropriately align the geometry of each tibial insert to a consistent coordinate system. Using principal component analysis (PCA) on the polygonalized data, each insert was reoriented so that the principal axis vectors (eigenvectors) of their respective covariance matrices were aligned with the Cartesian axes. The axial direction of the insert was aligned to the Cartesian z-axis. A second software utility was used to isolate and extract the articular or backside surface of the tibial insert, depending on the orientation of the input STL file. Triangular facets of the polygonal surface model were removed via thresholding if the z-component value of the outward surface normal for the constituent facets was above or below a user-determined criterion t where: $-1 \leq t \leq 1$. This process was repeated twice for each insert: First to isolate the articular surface and then a second time to isolate the backside surface. Six articular surfaces and six backside surfaces (one each from the averaged 9 mm, 11 mm, 13 mm, 15 mm, 18 mm, and 21 mm thick specimens) were therefore obtained (Fig. 2). Extracting the individual surfaces greatly decreased the file size of the geometries, reducing the largest (21 mm thickness) from 1.9 GB when intact to 450 MB for the articular surface extract; changing from ASCII to binary STL format further reduced the volume to 100 MB.

The same software utility described previously (Section 2.2) was then used to co-register and measure the deviations between the extracted surfaces across all combinations of the different thicknesses. This included 15 combinations for each of the articular and backside surfaces: 9 vs. 11 mm, 9 vs. 13 mm, 9 vs. 15 mm, 9 vs. 18 mm, 9 vs. 21 mm, 11 vs. 13 mm, 11 vs. 15 mm, 11 vs. 18 mm, 11 vs. 21 mm, 13 vs. 15 mm, 13 vs. 18 mm, 13 vs. 21 mm, 15 vs. 18 mm, 15 vs. 21 mm, and 18 vs. 21 mm. These deviations were plotted as a deviation map for each pair. Finally, all of the pairs were co-registered to produce a single deviation map for the articular surface and a single deviation map for the backside surface, in order to aid visualization of general trends. Registrations using only the extracted surface were much faster than using the entire geometry, taking less than 5 min to complete each registration and deviation map using a quad-core desktop computer with 8 GB of RAM, versus over 20 min for the intact geometry.

2.4. Worn insert test case

A new posterior-stabilized Genesis II tibial insert, size 3/4 and 11 mm thickness, was obtained for testing the implementation of this