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Computed Tomography Techniques Help Understand Wear Patterns in Retrieved Total Knee Arthroplasty

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ABSTRACT

Background: Suboptimal total knee arthroplasty (TKA) position of both femoral and tibial components is thought to be linked with poor clinical outcomes, polyethylene wear and the "unexplained" painful knee arthroplasty. The aim of this study was to better understand the effect of implant orientation on knee implant performance.
Methods: We analyzed 30 retrieved contemporary TKA implants. Implant positioning measurements in the coronal plane were made prior to revision using a diagnostic algorithm, based on 3D computed tomography (CT) images. Each retrieved polyethylene component was imaged using a micro-CT scanner and a high resolution computational 3D model of each component was digitally reconstructed. The difference in thickness between medial and lateral components was calculated. Statistical analysis was performed to investigate the association between component positioning and damage patterns.
Results: We found a significant correlation between both the tibiofemoral and femoral angles and difference in thickness between polyethylene compartments: varus angulations were strongly associated with thinner medial compartments, whilst valgus angulations were associated with thinner lateral compartments. Moreover, suboptimal tibiofemoral orientations and tibial component angulations were associated to greater differences in thickness between polyethylene compartments.
Conclusion: Our study is the first to compare accurate 3D CT measurements of prerevision TKA positioning in the coronal plane with postrevision retrieval analysis from innovative, accurate and highly reliable micro-CT–based method. Our results demonstrate the impact of component positioning on polyethylene damage and helps understanding of the in vivo performance of these implants.
Level of Evidence: III.

Polyethylene (PE) wear in total knee arthroplasty (TKA) remains a crucial issue. Aseptic loosening linked to periprosthetic osteolysis has been reported to be one of the main reasons for revision TKA [1,2]. Among the most common reasons for increased PE wear are malposition and malorientation. Suboptimal TKA position of the femoral and tibial components contributes to poor outcomes, premature PE wear, and persistent pain after TKA [3–6]. In particular, malposition in the coronal plane was considered to be related to early aseptic loosening, which was explained by increased PE wear due to abnormal force distributions [7,8].

In clinical practice, position and orientation of TKA is generally assessed using plain radiographs [9]. Several retrieval studies have assessed TKA implant orientation only by radiographs [7,10]. However, highly accurate measurements are strictly dependent on the patient's position during imaging, as this influences the resulting projection. In fact, well-aligned and reproducible anteroposterior and sagittal radiographs are rarely achieved. Moreover,

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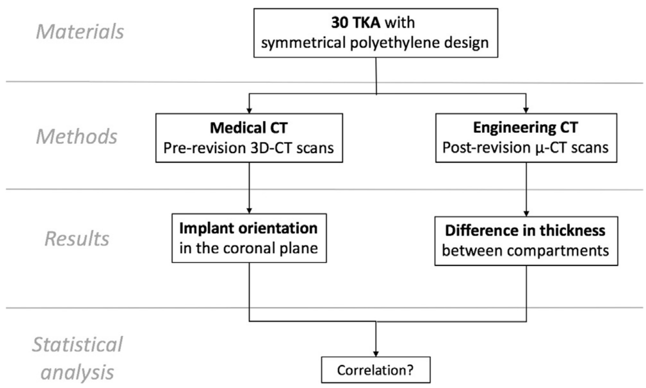

Fig. 1. Flowchart representing the steps of our study design.

measurements in the axial plane are not possible [11,12]. Routine assessment of TKA component position might also be performed on transverse computed tomography (CT) slices (2D CT) [6,13,14]. However, the identification of anatomical landmarks on the same CT slice is dependent on the orientation of the patient's limbs, anatomical variability, and CT slice width [15]. Hirschmann et al [11] recently demonstrated that the use of a low-dose 3D reconstructed CT is able to overcome these limitations.

Several retrieval studies have previously demonstrated the importance of TKA position for wear, but the clinical relevance of this relationship for long-term survivorship remains controversial [10]. This may be due to the method chosen to assess the PE wear pattern. Although previous papers [10,16] have used visual inspection and demonstrated that it can give an acceptable estimation about the quality of the damage, it may not be accurate enough to quantify the amount of wear [17]. Recently, the utility of alternative techniques, such as micro-CT scanning has been demonstrated [18,19].

The aim of this study was to correlate highly accurate measurement of prerevision TKA position on CT in the coronal plane, provided by an established 3D imaging technique [11], with retrieval findings postrevision, provided by a novel micro-CT–based method, to better understand implant orientation effects on knee implant performance.

Methods

Figure 1 shows the study design.

Materials

Our retrieval cohort consisted of 30 TKA with symmetrical PE tibial inserts, 22 were cruciate-retaining and 8 posterior-stabilized designs. They were obtained from 21 female and 9 male patients, with a median (range) age of 62 (43-78) years and a median (range) time to revision of 22 (5-162) months. The reasons for revision were instability ($n = 11$), malposition ($n = 9$), pain ($n = 3$), aseptic loosening ($n = 3$), patella maltracking ($n = 3$), and stiffness ($n = 1$). Table 1 summarizes the TKA and patient demographics for each case.

Three-Dimensional CT for Position Assessment

Prerevision CT scans of the knee from each patient were taken using the Imperial CT protocol [20]. This protocol allows a reduced radiation exposure by limiting the scanning to the mandatory fields including 3 anatomic regions, femoral head, knee, and ankle. This allows identification of the mechanical axes of both femur and tibia. Metal artifact reduction sequences were applied to accurately visualize TKA metal components and, consequently, measure implant orientations.

From the CT images, the mechanical axes of both femoral and tibial components were defined, the images orientated towards standardized frames of references and the following components' orientation measured [3]: (1) degree of varus/valgus of femoral component, measured as the angle between a line connecting the femoral component distal condyles and a line perpendicular to the mechanical axis of the femur, Figure 2A; (2) degree of varus/valgus of tibial component, assessed as the angle between a line connecting the horizontal face of the tibial component and a line perpendicular to the mechanical axis of the tibia, Figures 2B and 3 and the tibiofemoral angle, identified as the angle between the mechanical axis of the femur and the mechanical axis of the tibia, Figure 2C. The measured values were classified in agreement with surgical standard aims [21]; varus and valgus angles $>3°$ were considered suboptimal position.

This method proved to have a near-perfect intraobserver and interobserver variability (intraclass correlation coefficient [ICC] 0.96-0.99 and 0.89-0.97, respectively) [11]. This method is reproducible and more reliable than traditional methods, such as measurements on radiographs or 2D CT [11].

Micro-CT for Retrieval Analysis

The method consisted of 3 stages: (1) micro-CT scanning of our retrieved cohort and data reconstruction, (2) volumetric rendering from micro-CT data, and (3) analysis of 3D rendering. Figure 3 shows a flowchart explaining all the 3 stages of this micro-CT–based method.

Micro-CT Scanning and Volume Reconstruction

All PE inserts were scanned using a micro-CT scanner (XTH 225, Nikon Metrology NV), Figure 3B. Scans included 3176 views in 0.11° of increment, with one frame per view and a frame exposure of 1000 ms. The X-ray tube voltage was set to 80 kV, with a current of 300 µA. Scans were reconstructed at the full 45-µm isotropic resolution.

Volumetric Rendering

The volumetric rendering of each PE insert were analyzed with 3D micro-CT analysis software (Simpleware ScanIP, software version 7.0, Exeter, UK); isosurface rendering was performed, and the resulted geometry was saved in stereolithography file format, Figure 3C.

Volume Rendering Analysis: Difference in Thickness

Geomagic Control X (Geomagic Inc, Morrisville, NC) was used to further analyze all volume renderings. Each image of PE inserts was imported as measured data, and a plane was created and placed parallel and coincident to the back surface to serve as reference data, Figure 3D.

A 3D comparison between the tibial articular surface and the reference plane was then performed, and a color map representing relative distances was generated, Figure 3E. The thinnest point in both the medial and lateral compartments was identified, and the difference in thickness between them was computed, to establish the most deformed compartment. This deformation was considered as a combination of wear and creep; no distinction was made in the present study. This approach has been already adopted in previous studies [10,22]; compartment thickness was measured with calipers and considered a good estimator of the magnitude of wear. However, our method is based on micro-CT technology, which has been shown to be highly accurate [18,19]. Moreover, our method provided a high resolution (45 µm).

To assess the intraobserver reliability (degree of agreement among different measurements from the same rater), the ICC of 3 observations on 19 samples from the same rater was calculated. The