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Estimating regions of interest on the distal femur

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A B S T R A C T

We investigated the ability of a statistical shape model to estimate unknown regions of interest related to patient-specific unicompartmental knee replacement design on the distal femur. Generality ranged between 0.67 and 1.03 mm, specificity from 0.79 to 1.07 mm, and leave-one-out root mean square estimation errors from 0.88 to 1.27 mm for different regions. Moderate to strong correlations were established between ground truths and model estimates for local morphological measurements on the medial and lateral condyles. Results compared well to similar studies in the literature, and we conclude that shape models might prove useful during patient-specific unicompartmental knee replacement design.

1. Introduction

Unicompartmental knee arthroplasty retains as much of the joint's natural geometry as possible by only resurfacing the pathological parts. This could result in more natural kinematics compared to total knee arthroplasty under appropriate conditions [1,2]. Nevertheless, certain design limitations inherent in many current, off-the-shelf implants may cause a mismatch between the implant and normal or remaining portions of the knee. These include a predetermined range of sizes [3], similar shapes for both medial and lateral condyles [4] as well as poor implant fit [5]. This could undermine implant designs which attempt to emulate natural patient anatomy in order to restore normal joint motion [6,7].

Patient-specific implants aim to address such shortcomings and restore an individual's knee to its pre-pathological and corrected state, focusing on improved fit and more natural post-operative kinematics [3,8–10]. In general, the design workflow of such implants is similar to that of commercially available patient-specific instrumentation [9,11]. First, tomographic scans such as MRI or CT are acquired pre-operatively to visualise the affected geometry. This is followed by segmentation of the various geometries from which 3D surface meshes may be generated. Finally, computer aided design software is used to develop the implant geometry and to test the fit in silico.

However, the design of a patient-specific unicompartmental knee replacement has some unique challenges, one of which was the focus of this work: what is 'normal' geometry given a mesh of a pathological knee? A healthy contralateral knee is not always available [12], and if it is, duplicating scans increases cost as well as radiation exposure in the case of CT.

We therefore proposed the use of statistical shape models to estimate the healthy region of interest as a 3D surface, between the segmentation and design steps [13] as indicated in Fig. 1. Statistical shape models are deformable models based on the variation of shape within a population, with the defining characteristic that these models can only deform in ways captured by the training data [14]. They have seen extensive use in extrapolating 3D anatomical structures from partial observations [15], including 2D radiographs and fluoroscopic images, obscured ultrasound scans and locally digitized points [16,17], and even pathological geometries [18,19].

The objective of this study was to conduct a preliminary investigation into the ability of a statistical shape model to estimate, given some partial input, the healthy regions of an individual's knee that pertain to unicompartmental knee replacement design. Towards that end a model was built from a database of twenty manually segmented MRI scans of healthy distal femurs and partitioned into regions of interest. We evaluated our results by investigating the global surface based metrics of the reconstruction as well as local morphological measurements compared to the respective known input shapes. This work forms part of the patient-specific implant development effort at the Biomedical Engineering Research Group of Stellenbosch University.

Abbreviations: 2D, two-dimensional; 3D, three-dimensional; CT, computed tomograghpy; MRI, magnetic resonance imaging.

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Annotations

fAC	femoral anterior condyle
fAPLd	femoral antero-posterior lateral distance
fAPMd	femoral antero-posterior medial distance
fAr	femoral anterior radius
fAS	femoral articular surface
fFS	femoral full shape
fINA	femoral intercondylar notch apex
fLC	femoral lateral condyle
fLr	femoral lateral radius
fLTS	femoral lateral terminalis sulcus
fMC	femoral medial condyle
fMLAa	femoral medio-lateral anterior angle
fMLDa	femoral medio-lateral distal angle
fMLPa	femoral medio-lateral posterior angle
fMTS	femoral medial terminalis sulcus
fMr	femoral medial radius
fTEDd	femoral trans epicondylar distance

2. Materials and methods

2.1. Data

Right knee MRI scans of twenty white South African (eight male and 12 female) subjects ranging in age from 16 to 57 with a mean of 30.9 years were used retrospectively in this study. Ethical clearance was obtained from the Faculty of Health Sciences (Stellenbosch University, South Africa), and subjects were selected to be skeletally mature with normal, asymptomatic osseous and cartilaginous geometry. The raw slices used had thicknesses of 1.5 mm with a resolution of 512 × 512 pixels in the sagittal plane, and pixel sizes ranged from 0.38 to 0.47 mm with a mean of 0.4 mm. The distal femur in each scan was segmented in the sagittal plane by a single expert using Mimics software (Materialise, Leuven, Belgium) according to the following protocol in order to reduce observer bias:

1. An initial threshold was manually adjusted in order to isolate the femur, depending on the gray values.
2. The threshold results from every second slice was manually cleaned and edited using a series of operations like cropping, erasing unwanted artefacts and closing the mask in portions with poor contrast.
3. The mask was interpolated between the edited slices and used to generate a 3D surface mesh of the femur.
4. The mesh was smoothed to remove any artefacts.
5. A mask was recreated from the mesh, and validated against the original scans.
6. A stereolithography file that contained the mesh of the femur as face-vertex data was finally exported.

2.2. Coordinate system

The resulting mesh of each distal femur was transformed spatially to a coordinate system based on that of Grood and Suntay [20]. Selection of the anatomical landmarks and axes used were based on reported values of precision [21] and were performed directly on the 3D surface mesh rather than the raw scan images. The femur's medio-lateral or x-axis was defined parallel to a line connecting the centres of spheres fitted to its condyles between 0° and 115° flexion [22], with lateral taken as positive for right knees. The coronal plane was defined parallel to both this line and the femur's anatomical axis, containing the x-axis and its orthogonal, the cranio-caudal or z-axis with positive defined cranially. Following the right-hand rule, the antero-posterior or y-axis was taken as orthogonal to both the x and $z$axes, the anterior direction being positive. These axes passed through the origin on the femoral intercondylar notch apex (fINA).

2.3. Sampling and regions of interest

Each distal femur was isolated from the remaining geometry present in the scan window by performing a plane cut along its shaft. The position of the cut was offset half of the Euclidean norm between the antero-posterior and medio-lateral distances from the most distal point on the femur.

Following this, Poisson disk importance sampling as per Corsini et al. [23] was performed on the coordinate aligned mesh of each femur in order to obtain a dense set of 3D points. This was achieved by first oversampling the mesh using the streaming Monte Carlo algorithm and then paring away all neighbours within a sphere about randomly selected points. The maximum sphere radius given a target number of sample points was determined from the densest possible packing of disks on a plane, a hexagonal lattice structure [24]. The radius for each randomly selected point was further adjusted based on the absolute of the mean mesh surface curvature so that the sampling distribution would mirror the femur's local information density. By multiplying the maximum

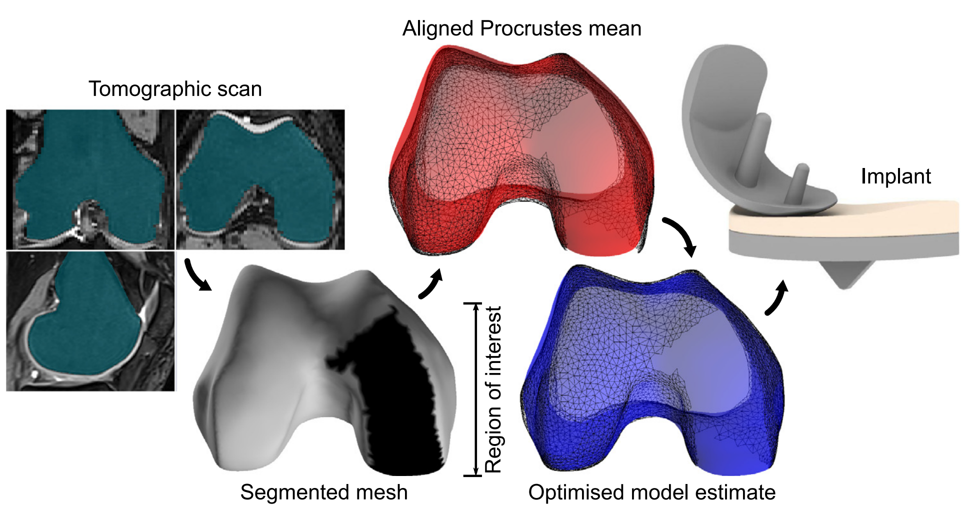

Fig. 1. Proposed patient-specific implant workflow.