INTRODUCTION

Fluoroscopic imaging techniques have been used extensively to measure in-vivo kinematics of total knee arthroplasty (TKA) because of the relatively low radiation dosage and the accessibility of the equipment. Previous studies employed a single fluoroscope to take sagittal plane images of the knee at multiple flexion angles. Using the geometry of the fluoroscope, three dimensional (3D) computer models of the components were matched to the two-dimensional (2D) features of the acquired fluoroscopic images. For increased accuracy an additional fluoroscope is added to reduce out-of-plane error [1]. This study presents an algorithm and its accuracy for automatically matching projections of 3D TKA models to two orthogonal planar images of TKA components acquired with a dual-orthogonal fluoroscopic imaging system.

METHOD AND VALIDATION

A dual-orthogonal fluoroscopic system (Fig. 1) was used to acquire images of the knee at various flexion angles. The images were then automatically segmented using Canny edge detection and corrected for distortion using the method of Gronenschild. Edge detected points of the TKA components were then used to create spline curves, using a periodic spline algorithm.

Next, a virtual replica of the dual-orthogonal fluoroscopic system was constructed. Using the calibration data, two virtual source-intensifier pairs were created in a solid modeling program (Rhinoceros®, Robert McNeel & Associates, Seattle, WA) and oriented so that their relative positions replicated the geometry of the real fluoroscopic system (Fig. 2).

The splines of the TKA fluoroscopic images were then placed on their respective virtual intensifiers. Next, point clouds were made from the manufacturer's TKA CAD models and introduced into the virtual system. A local coordinate system was created for each point cloud model and mapped to the global coordinates of the virtual fluoroscopic environment using a position vector and rotation matrix.

Using this virtual setup an automated matching algorithm was formulated as an optimization procedure that minimized the error between projected model silhouettes and actual fluoroscopic image outlines in order to determine the model pose. The objective function is expressed as a scalar function with six independent variables defining the origin of the local coordinate system and the three Euler angles of the local system in the global system. The scalar function value is the average distance between the 3D projected model silhouettes and the segmented fluoroscopic outlines. Minimization of this function was accomplished with the Broyden, Fletcher, Goldfarb, and Shanno (BFGS) quasi-Newton method and implemented in Matlab software.

A rigorous validation of the automatic matching algorithm was performed to demonstrate the accuracy and repeatability of recreating the TKA pose. Validation consisted of running the algorithm with idealized, controlled, and in-vivo data using ten randomly generated initial pose estimates for each test. The idealized data set was created by replicating the fluoroscopic environment with the 3D solid modeling software and synthesizing fluoroscopic images of TKA components in a position approximating a deep knee bend. The controlled data set consisted of images of eight spheres 12.70±0.01 mm in diameter in a fixed pattern. The in-vivo data set test consisted of in-vivo images taken with the dual fluoroscopic system of the right knee of a patient after TKA. The patient had a cruciate retaining component and images were taken during a lunge (NexGen CR TKA, Zimmer, Inc, Warsaw). Poses selected for matching were for images taken at 10° and 50° of flexion of the patient.

RESULTS

Accuracy for the idealized tests was measured as the error between the body fixed local coordinate systems of the golden standard and the matched models. The standard deviation was selected as the measure of repeatability. Pose for the femoral component was recreated to within 0.02±0.01 mm and 0.02±0.02° for a medium point density model. Results for the tibial component were 0.07±0.04 mm and 0.16±0.10° for the medium point density model. For the controlled tests, the distance between each adjacent pair of spheres was calculated. The average distance between matched pairs of adjacent spheres was 12.69 mm, 0.01 mm less than the actual distance data, with a standard deviation of 0.06 mm. Results from the in-vivo data sets had a maximum translational deviation for both poses of ±0.12 mm for the femoral component and ±0.29 mm for the tibial component. Maximum angular deviation for both poses was ±0.12° for the femoral component and ±0.25° for the tibial component.

DISCUSSION

The results of these tests gave an empirical measure of the accuracy and repeatability of the automatic matching algorithm and insight into the factors affecting convergence of the algorithm. It was found that higher model point densities resulted in improved repeatability and increased rotational accuracy. Increasing the number of projected outline points used in matching improved convergence of the algorithm; however, it did not improve accuracy. Lastly, small or large perturbations to the initial pose guess gave similar results, showing that the automatic matching process is forgiving of the initial pose estimate and allows for minimal operator intervention. This method compared favorably to previous fluoroscopic methods for determining the pose of 3D objects from 2D. The method has been shown to be robust and accurate. This methodology could be a useful tool for investigating in-vivo dynamic TKA kinematics and can be readily applied to the investigation of in-vivo motion of other musculoskeletal joints, such as the elbow, shoulder, and ankle.

REFERENCES


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