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2D ICP-BASED ROBUST 2D-3D REGISTRATION FOR BI-PLANE FLUOROSCOPIC ANALYSIS OF SKELETAL KINEMATICS

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Introduction

Accurate measurements of the relative motions between the skeletons in human joints help understand mechanical pathways of joint disease. Recently continuous X-ray imaging, called fluoroscopy, has been adopted in biomechanical studies for accurate measurements of skeletal kinematics. In bi-plane fluoroscopic analysis a pre-processed three-dimensional (3D) polygon model of a skeleton from computed tomography is registered to two X-ray images to find skeleton's 3D position and orientation in the laboratory space, which is the 2D-3D registration.

Numerous edge-based and area-based 2D-3D registration methods have been studied to increase the convergence range, accuracy, and speed [1]. Optimization-based methods minimize the difference between the edges in X-ray image and the edges of a target object projected onto the X-ray image plane by optimizing three rotational and three translational variables [1]. The iterative closest point (ICP) method has widely been used to process 3D laser scan data by aligning partially scanned data of an object [2]. In this study we propose a 2D ICP-based robust 2D-3D registration, whose performance was compared with a conventional optimization-based 2D-3D registration.

Methods

A cadaveric knee was prepared. Five metallic beads were implanted in the femur. The knee was flexed from full extension to 90 degree flexion, and bi-plane X-ray images were recorded for fifty-nine frames. A 3D femur model was obtained from the CT data of the knee. A geometric calibration of the bi-plane system was performed using custom software.

The primary standard of the pose of the femur was obtained from the reconstructed 3D coordinates of the implanted beads. The X-ray images were pre-processed to make boundary edge images of the skeleton to reduce factors affecting the comparison of the registration performances between the proposed method and a optimization-based method. All image data and calibrations were loaded into custom software written in Matlab for automatic registration

The initial pose of the femur for the first frame was manually determined and provided to both methods. In the second and later frames the pose in the previous frame was used as the initial pose for pose estimation. In the proposed method the femur model was projected onto each X-ray image plane to create silhouette images. The points on the silhouette were registered to the femur boundary edges in the X-ray image using 2D ICP. Thus the following 2D rotation and translation matrices were obtained for each of the two planes, plane A and B.

$$\mathrm{T}_{2\mathrm{d}}^{\mathrm{A}} = \begin{bmatrix} \mathrm{R}_{2\mathrm{d}}^{\mathrm{A}} & \mathrm{t}_{2\mathrm{d}}^{\mathrm{A}} \\ 0^{\mathrm{T}} & 1 \end{bmatrix}, \qquad \mathrm{T}_{2\mathrm{d}}^{\mathrm{B}} = \begin{bmatrix} \mathrm{R}_{2\mathrm{d}}^{\mathrm{B}} & \mathrm{t}_{2\mathrm{d}}^{\mathrm{B}} \\ 0^{\mathrm{T}} & 1 \end{bmatrix}$$

One hundred points were sampled from the femur model at the initial pose and were projected onto both planes. The projected points were 2D transformed in the planes according to T_{2d}^{A} and T_{2d}^{B}, respectively. Lines connecting the X-ray source position and the transformed points were created. Thus for a sampled point from the femur two 3D lines were created and their intersection point was calculated. The rotation and translation from the initial locations of the sampled points to the intersection points could be obtained, which is the approximation of the actual rotation and translation of the femur from the initial pose.

The pattern search command in Matlab was used for the optimization-based method. Six parameters, three for translation and three for rotation using the exponential map of a quaternion, were considered while minimizing the average distance between the silhouette of the 3D model and boundary edges extracted from X-ray image for the two planes.

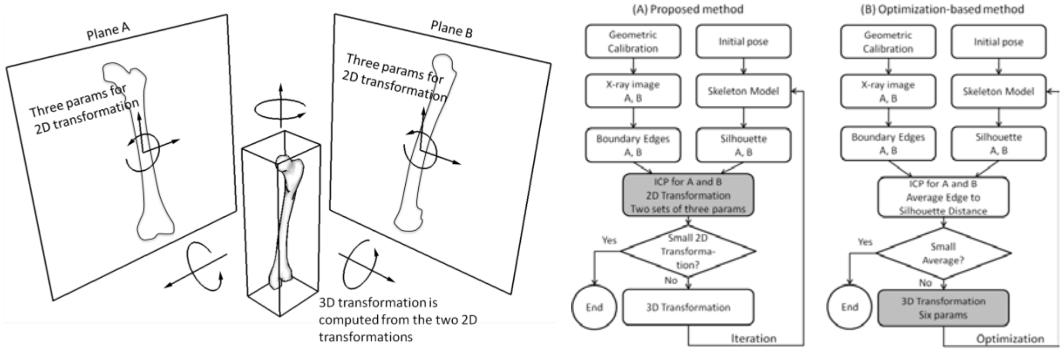

Figure 1 Geometric set-up of the model and two X-ray image planes (Left); Proposed method of calculating 3D transformation from 2D ICP in plane A and B; This process is iteratively applied until it converges (Left (A)); Procedures of the optimization-based method was very similar to the iterative method but it considers six parameters in every cycle.

Results and conclusion

A cycle took 0.21 ms and 0.17 ms for the proposed method and the optimization-based method, respectively. In average the proposed method took 7.1 cycles and the optimization-based method took 311.5 cycles for a frame. The average translation and rotation differences were calculated using the helical axis and were 1.5 ± 1.3 mm and 8.1 ± 1.0 degrees between the proposed method and the primary standard, bead-based registration. The optimization-based method started losing the track of the object from around 38th frame and diverged.

The proposed method showed large convergence range and very short cycles compared to the optimization method. The accuracy was relatively low. Thus the proposed method can be used as the initial pose estimation before running the optimization method which has smaller convergence range but good accuracy.

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