NOVEL PATH PLANNING METHOD FOR C-ARM IMAGE BASED DISTAL LOCKING OF INTRAMEDULLARY NAILS

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INTRODUCTION

Currently the most common treatment for long bone fracture fixation is implanting an intramedullary nail into marrow cavity of the long bone. Usually the distal locking holes are hard to be located because they are visible only under X-ray exposures and the nail deforms during the implantation process. So the surgeon must rely on fluoroscopy images to locate distal locking hole during operation. Conventional distal locking methods are based on C-arm images (Viant, et al. 1995, Zhu, et al. 2002, Neatpisarnvanit, et al. 2006), mechanical instruments (Windolf, et al. 2012), conventional down-the-beam method with tracked instrument (Diotte et al. 2014), sensors (Hoffmann, et al. 2012), nail pose estimation (Yaniv, et al. 2005), and optimization method with single C-arm image, (Zheng, et al. 2007). Most of them will need to capture more than two C-arm images or bundle with its instruments for finding hole positions. This paper presents a new planning method for C-arm image-based distal locking of intramedullary nails, which can locate the positions and axial directions of distal holes by using only one fluoroscopy image, and can be used to assist surgeons to complete hole-drilling process. A simulation based on 3D Computer Graphics has been done. The mean position error is 0.63 mm, and the mean axial direction error is 0.73 degree.

MATERIALS AND METHODS

To assist the surgeon go through distal locking procedure with a C-arm image based navigation system, the central position and axial direction of locking hole should be located first. The path planning method developed for distal locking consists of two parts: 1) determine the axial direction of locking hole and 2) locate its central position.

1) Determination of the axial direction of locking hole

The C-arm x-ray projection can be considered as a pinhole projection model with distortion (Fahrig, et al. 1997, Gorges, et al. 2005), and arguments of projection model are available from the C-arm specification or determined by a self-developed C-arm image assisted navigation system, which can be set up in 10 minutes prior to operation.

Figure 1-a shows the pinhole projection of an intramedullary nail with two locking holes. The image contour of the locking hole appears to be an ellipse. Figure 1-b is a simulation of projection images of a series of coplanar locking holes. Based on 3D geometry and perspective projection, when the projected contour of locking hole gradually becomes a circle from an ellipse, the vector from the x-ray focal point to the center of the circular contour can be thought as the axial direction of the locking hole and the circular contour center is the projection of the locking hole center. Figure 1-b shows that the vector of minor axis of the projected elliptic contour passing through the contour centroid will intersect at the virtual circular center. So the virtual circular contour center can be determined by computing the intersection point of the ellipse's minor axes of the two locking holes, as illustrated by Figure

1-c. (The potential minor error is caused because the plane of the simulated locking holes is not parallel to the C-arm image plane).

To locate the virtual circular contour center on the C-arm image, first, using image processing algorithm to segment the contours and its centroid of projected locking holes. Second, principle component analysis algorithm (PCA) is applied to determine the second major axis (minor axis) of each contour and compute the intersection point (the projection point of hole center) of two minor axes. Finally, the vector from the x-ray focal point to the intersection point is the axial direction of the locking hole.

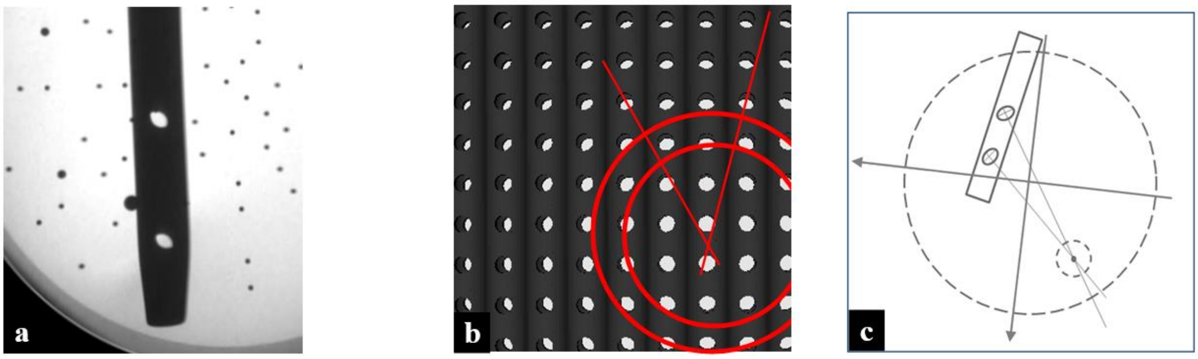

Figure 1: (a) C-arm image of distal locking holes. (b) Image regularity of locking holes. (c) Relationship between the minor axes of the elliptic contours and the virtual circular contour.

2) The center position of locking hole

The vector between the centers of two locking holes can be determined by computing the cross product of the axial vector of the locking hole and the normal vector of the plane which is determined by the x-ray focal point and the two contour centroids of locking holes. Then the distance from the x-ray focal point to each locking hole center can be computed by using the law of sines. The line equation from the focal point to each contour centroid can be determined, and this line also passes through corresponding locking hole center. Each locking hole center can thus be located because the direction and distance between x-ray focal point and hole center are known.

3) Experiments

We designed an experiment to simulate and quantify the position and direction accuracy by setup a C-arm image projection simulation program (simulator) with a 3D intramedullary nail model. The C-arm image projection simulator is an OpenGL rendering pipeline based on real C-arm arguments, i.e., focal length, image size (pixels) and real pixel physical size measured by a self-developed C-arm image assisted navigation system. So the C-arm image simulator can be considered as a real C-arm projection model without image distortion. The 3D intramedullary nail model is designed according to the specification of a real intramedullary nail. The simulation program will perform the following steps automatically: 1) Place the 3D intramedullary nail model at a randomly generated position and axial direction in the C-arm image simulator. 2) Render 3D scene. 3) Capture the rendering scene result as a C-arm image. 4) Apply the axial direction and center position locating method. 5) Calculate the errors between the inputted and computed positions and axial directions.

RESULTS

A total of 20,000 cases were performed in the simulation experiment for accuracy assessment. The average position error of the locking hole center is 0.63 ± 0.54 mm while the average axial direction error of the locking hole is 0.73 ± 0.54 degree. The experimental results are showed in Figure 2. And there were some failed cases which were caused by too small contour area, e.g. contour area < 20 pixels, which the PCA algorithm could not obtain a proper second principle axis and the intersection point of two minor axes will not locate at the virtual circular contour center. The factor that caused small contour area is the large intersection angle between the locking hole axis and the x-ray optical axis of the C-arm.

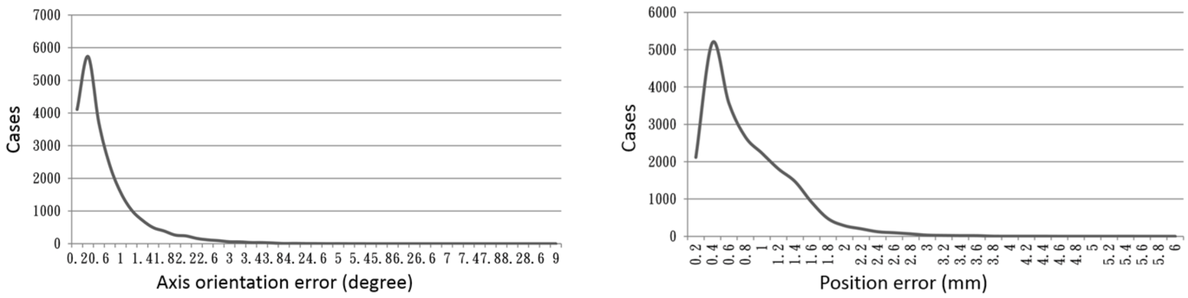

Figure 2: Distribution of axial direction errors and position errors

DISCUSSION

Simulation based methods (Neatpisarnvanit 2006) need two or more C-arm images taken at different positions, instruments based methods (Windolf, et al. 2012) need external instruments mounted with the nail. Zheng and Zhang (2007) presented a method based on optimization method with one C-arm image, which took 10~30 seconds to complete the process. The advantages of the proposed method are that it can be performed with one C-arm image in less than 5 seconds and doesn't need additional instruments. According to the experimental results, the novel path planning method for distal locking of intramedullary nails should satisfy the needs of practical applications.

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