GENERALIZED FEATURE-BASED RSA OF ORTHOPAEDIC IMPANTS

Paul A. Thistlethwaite (1), Janet L. Ronsky (1), H.S. Gill (2)

(1) University of Calgary, Department of Mechanical and Manufacturing Engineering, Calgary, Canada (2) Nuffield Department of Orthopaedic Surgery/OOEC, University of Oxford, Oxford, UK

INTRODUCTION

Roentgen stereophotogrammetric analysis (RSA) is a measurement method that can provide quantitative information for the objective evaluation and comparison of orthopaedic implant migration. Migration calculations rely on the ability to determine the position and orientation of implant components. To provide this functionality, RSA requires either a marker based approach, which requires the modification of each implant component by the addition of spherical markers, a model-based approach, which requires accurate 3D models of each component, or a feature-based approach, which requires special inherent implant features. Together, these techniques provide the ability to perform RSA on almost any implant, but they also have several limitations. A new RSA method to determine implant position and orientation without the requirement for modification, or accurate 3D models is described. This method is an extension and generalization of more specific feature-based methods and is based on the geometric inter-relationship between image and feature pairs.

Current methods and limitations

Traditionally, spherical radio-opaque markers are attached to implant components and inserted into the host bones to define these objects for kinematic measurements. One limitation of this technique is that markers can be obscured by metallic components of the implant rendering them invisible in x-ray images. Also, the addition of markers to an implant is often impractical with prohibitive certification and cost implications. Newer methods exploit specific geometric features and eliminate the need for additional markers but have limited applicability to a few specific types or classes of implants. The most general marker-less approach, the model-based approach [1], substitutes the need to modify implants with the need to acquire an accurate geometric model of each implant. This method is also geometrically limited by manufacturing tolerances and can be time consuming.

METHODS

Two general relationships can be exploited in a feature-based RSA method. The first arises from the ability to visualize and characterize matching implant features between x-ray images, and the second arises from photogrammetric principles. An implant feature is characterized to some degree by its contour, which can be identified and separated from the x-ray image using Canny edge detection [2]. The 3D position and pose of the implant can be derived by augmenting this contour information with photogrammetric information. The required photogrammetric relationship is determined by a calibration process that defines the mathematical transformation between each 2D image and the corresponding 3D space. Together, these yield the fundamental matrix, and the epipolar geometry that inter-relate the two images. Epipolar geometry defines a plane by three points (Fig. 1); two epipoles (e1,e2) that are known from the calibration, and any single image point (x1). This plane is coplanar with the plane containing the two x-ray foci and the 3D point that produced the image point. This plane intersects the second image on the epipolar line. The projection of the 3D point (X) on this image (x^2) will lie on this line.



Figure 1: The epipolar relationship for an RSA arrangement. The points (*X*, *F1*, *F2*, *x1*, *x2*, *e1*, *e2*) are all coplanar.

By selecting a contour point on one image, and using both the epipolar and feature relationships, a single matching point can be determined. This unique point exists at the intersection of the epipolar line and the feature contour. Once a pair of matching points is determined a 3D point can be reconstructed. Several 3D points generated in this manner points kinematically define the implant.

Validation

A Trilogy[©] metallic acetabular shell (Zimmer, USA) was used to validate the method. Two simple geometric features of the cup were exploited with the generalized feature-based RSA method: the hemispherical shell and the planar base circle. The visible portion of the base circle outline defined a unique ellipse on each image, the parameters of which were determined by a least squares fitting method [3]. Points on this feature curve in one image produced epipolar lines that intersected the feature curve in the second image (Fig. 2). Since the matching points had to lie on this line and also on the feature curve in the second image, any intersection of these two entities produced a potential match. For the elliptical curve there were two intersections (x^2, x^2) for each original point (x^1) and therefore two possible reconstructed 3D points. Multiple reconstructions were performed and the points separated into two sets, which were planar fit to define two degrees of freedom for the cup via the planar normal vector. The projection of the center of the hemispherical feature was reconstructed to a 3D point that defined an additional three degrees of freedom. The last degree of freedom, angular position about the axis of symmetry, could not be determined by either of these two features.



Figure 2: The intersections of an epipolar lines and feature curve (x_2, x_2) provide possible matching points for a selected point (x_1)

Six stainless steel spherical markers were rigidly attached to the acetabular shell via acrylic rods. The rods placed the spherical markers outside the radio shadow of the cup and were used for a marker-based definition of the cup. A custom jig assembly allowed the cup with attached markers to be positioned in either approximately 30 or 50 degrees of tilt and 10 or 20 degrees anteversion with respect to the jig base. Eleven rigidly fixed markers defined the base, which emulated a human pelvis. The cup position and pose was determined by a Bright[®] (Mitutoyo, Japan) coordinate measuring machine and used as the baseline definition for comparing the RSA measurements. RSA determinations of position and pose were calculated using both the generalized feature based method and the marker-based method. Coordinate transformation into a common reference frame were performed using the Soderkvist algorithm [4].

The RSA arrangement was calibrated using a biplanar cage with an approximate volume of 35x35x40 cm, which enclosed the positioning jig. A pair of x-ray exposures were taken for each of the four cup positions and a minimum of 20 calibration markers were visible in each x-ray image. The resulting films were digitized on a Scanmaster DX (Howtek, USA) x-ray scanner at a resolution of 300 pixels per inch edge detected and processed. The complete RSA process from x-

ray image data to position and orientation results and statistics was implemented in Matlab (The Mathworks Inc., USA).

<u>Results</u>

Method		Position (mm)			Orientation (deg.)	
		Х	Y	Z	Tilt	Anteversion
Marker-based	Mean Error	0.019	0.001	0.017	-0.168	0.138
	95% C.I.	±0.046	±0.073	±0.046	±0.179	±0.149
Feature-based	Mean Error	0.010	0.000	0.005	0.093	-0.087
	95% C.I.	±0.043	±0.064	±0.069	±0.183	±0.149

The measurement error for each of the five degrees of freedom was defined as the difference between the RSA based measurements and the CMM based measurements. The mean error for each degree of freedom was the average of the measurement error over the four trials. A t-distribution with t=3.1824 was used to obtain the 95% confidence interval for the measurements.

DISCUSSION / CONCLUSION

These results demonstrate that the generalized feature-based RSA method compares favorably with the marker based RSA method for position and pose determination for metal backed acetabular cups. The mean errors were lower in all cases and the 95% confidence intervals were similar. The generalized feature-based RSA method produces similar or slightly improved results to the cup position and pose method proposed by Valstar [5] who reported maximum errors in position of 0.09 mm, 0.07 mm and 0.34 mm along each axis and mean errors in pose determination of 0.41° with a confidence interval of $\pm 0.13^{\circ}$. By comparison, the maximum position errors for the feature based method were 0.05 mm, 0.06 mm and 0.07 mm along each axis while the largest mean pose error was $0.06^{\circ} \pm 0.18$.

The new generalized feature-based position and pose determination method has been proven as a simple and accurate alternative to the more commonly used discrete marker based method. This method is also methodologically simpler and more direct (non-iterative) than both model based and more specific feature-based methods. The new method is easily applied, as it uses the same paradigm for 3D measurement and same primary algorithm as used for markers, which is already a part of the code in a marker-based RSA program. This method can be extended to use a variety of other implant features and therefore facilitate marker-less RSA for a number of implants without the need for accurate geometric models of each specific size and type.

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