Analysis of Total Hip Replacements Using Active Ellipses

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Abstract. In this paper we propose a new method for the measurement of wear of a total hip replacement. Our method exhibits a greater degree of automation and is to be both accurate and repeatable. Measurement of wear can be quantified as the displacement of the centre of the femoral head relative to the centre of the acetabular cup or acetabular rim. Our method uses active ellipses - ellipses that, with prior knowledge of the intended contour, search for and alter shape to segment the boundary of the head and rim.

A set of radiographs are manually annotated and the characteristics of the boundary of the femoral head and acetabular rim are learned. Two ellipses are sequentially placed on the radiograph, the first deforming around the boundary of the femoral head, the second placed using the previously learned average shape of the acetabular rim and converges around the wire marker. Once both ellipses have converged the distance between their two centres can be calculated and converted to mm as a measure of wear.

Our method is validated by comparison with manual fitting of ellipses. A discussion of the results, the clinical relevance and further investigations concludes this paper.

1 Introduction

With over 40,000 total hip replacement (THR) operations performed annually within the UK and over 5,000 of these are revisions [1]. There are clear benefits for providing early detection of implant failure and evaluation of surgical techniques and implant designs. The majority of failures are due to the displacement of the centre of the femoral head relative to the centre of the acetabular cup (see Fig 1a). Current findings are that the latter occurs most frequently [2]. The aim of this research is to create a new, automated method for the analysis of total hip replacements (THRs) that is more automated, precise, accurate and repeatable than existing methods.

Analysis of THRs is conducted by a variety of methods including manual methods such as overlaying concentric circular transparencies on the radiograph and annotation via pencil and rulers on the film or a digitizing tablet. Another method of analysis is roentgen stereophotogrammetric analysis (RSA) [3] which requires the insertion of markers used as reference points in follow up X-rays. As the markers are inserted during the operation it cannot be used retrospectively. Semi-automated image processing techniques have been implemented [4] [5]. These techniques use edge detection but do not use any prior knowledge of the distinct contour of the femoral head or wire rim and require considerable user interaction. Also of note is Cootes and Taylor's Active Shape Models (ASM), deformable models that are trained from previous examples to locate structures from computer images - including hip implants [6]. It is unclear however how they are to be used for the measurement of wear.

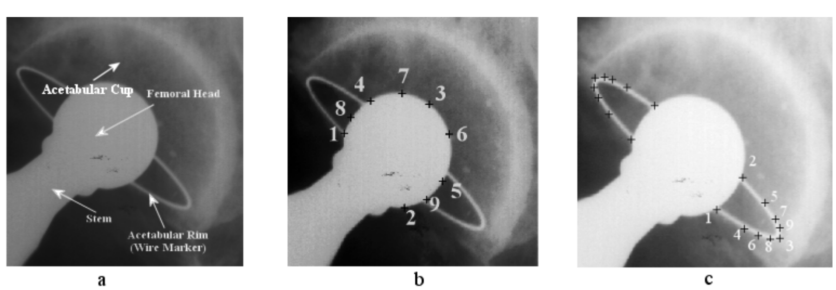

Figure 1. a) A radiograph of the Zimmer CPT prosthesis. b) Annotation of the femoral head with 9 approximately equi-spaced points, numbers correspond to the order of annotation. c) Annotation of the acetabular rim with example of order of annotation on right wing of rim, points are concentrated in areas of high curvature.

2 Method

Our method uses active ellipses and the normalized first order derivative of the grey levels of the femoral head and the acetabular rim from a set of manually digitized and annotated radiographs. Models of the grey level around the boundary of the femoral head and the acetabular rim are created. With these models searches can be undertaken

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on unseen images, locating first the elliptical contour of the femoral head and then that of the acetabular rim, and computing the Euclidean distance between the centres of the two ellipses.

2.1 Head and Rim Models

It is necessary to have a training set of the radiographs before beginning analysis with this method. For each image in the training set, landmark points are annotated on the edge of the femoral head, equi-spaced over the elliptical portion by taking the midpoints between existing points as shown in Figure 1b. A second annotation is required for the rim wire with points concentrated in areas of higher curvature to ensure an accurate fit, (see Fig 1c). A least squares (LS) ellipse fit is performed on the points from each femoral head and on each acetabular rim [7]. $2k_1 + 1$ pixels centered on the ellipse are sampled along N normals. Separately for the femoral head and the acetabular rim the normalized first-order derivative profile is calculated along each normal. Again separately for the femoral head and the acetabular rim a covariance matrix and a mean profile are determined from all the training examples. This results in two distinct models, one for the femoral head and one for the acetabular rim (see Figure 2). Additionally the mean axis and orientation of the rim is calculated and stored.

Once the system is trained an ellipse is placed within an unseen radiograph, requiring the operator to select one starting point, ideally on the centre of the femoral head. The system will search along extended normals to the ellipse of length m pixels each side (where $k < m$).

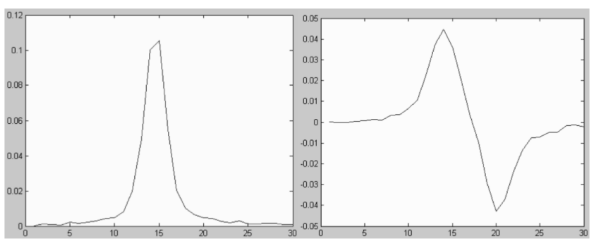

Figure 2. The average normalized derivative profile of the boundary of the femoral head (left) and at the wire marking on the rim (right). Covariance matrices were also estimated but are not shown.

2.2 Ellipse Searching

By taking normalized grey level derivative profiles of length k_1 along the search line and using the mean and inverse covariance modelling of the head the Mahalanobis distance can be computed between each possible point on the search line and the model. The Mahalanobis distance is used as it is a measure of the difference of the current profile from the mean profile of the model taking into account variation around the mean from the training set (see Figure 2).

The point on each search line with the smallest distance is stored. Once all search lines have been considered 25% are discarded that are assumed to be points in the neck of the prosthesis where there is no edge strength. The remaining points are stored and a least median squares fit (LMedS) [8] is performed to them. LMedS is regarded by Rosin et al. as the most reliable robust fitting method. LS fitting is highly sensitive to outliers while LMedS can provide accurate results with up to 50% outliers.

2.3 Locating the Head and Rim

A new ellipse has then generated with the centre chosen by the user. Searching is repeated until this ellipse converges around the contour of the femoral head. Convergence is defined by the new parameters of the ellipse only differ from the previous parameters (major axis, minor axis, centre co-ordinates and orientation) by a vector of five predetermined thresholds, one for each ellipse parameter, t_1.

As it is assumed the head is now found, a binary mask is created wherein all points within the ellipse of the head are set to true. The ellipse in the mask is dilated or enlarged slightly to prevent points on the femoral head being chosen again. A second ellipse is now placed using the centre of the head ellipse but the average axes and rotation of the rims in the training set are used. A second search is conducted, this time using normals of length k_2 and m_2 and the mean and inverse covariance for the rim. Any points found within the femoral head, by comparison with the binary mask, are discarded. This is done because the boundary of the head is a strong edge and normals where there is no wire rim to detect choose this, and may in extreme cases exceed the outlier tolerance of LMedS. An LMedS fit is performed on the remaining points until convergence occurs within a second vector of thresholds t_2.

Once the two ellipses have converged it is trivial to find the Euclidean distance between their centres, and given the known diameter of the femoral head conversion can take place from pixels to mm.

2.4 Experimental Preparation

The method described above was implemented as a Matlab routine. In order to validate it our training set consisted of 45 postoperative radiographs. Our test set consisted of 30 Year 1 radiographs. Both sets were radiographs containing Zimmer CPT prostheses with a 22.225mm diameter head, the preferred model at Ninewells Hospital, scanned at 150 dpi (see Fig 3a).

As a means of comparison to our method, analysis was conducted on the test set by having a practitioner highlight 9 landmark points on the femoral head and 18 on the acetabular rim (see Fig 1). A LS fit was done to each set of points and the Euclidean distance between the centroids was calculated in pixels. Each radiograph was measured twice, with a week between each measurement. At this stage 5 radiographs where acetabular rim was non-elliptical (see Fig 3b) were rejected.

For our method two measurements were made on the same radiograph with differing start positions. The system did not return a value on 2 additional examples due to the acetabular rim ellipse being particularly eccentric (see Fig 3c).

The following values were used for the search parameters:-

t_1 = [0.5,45^o]; t_2 = [0.5,6^o]; k_1 = 15; k_2 = 15; m_1 = 95; m_2 = 45; N = 200.

As the ellipse we intend for is almost circular, the orientation criteria in t_1 is almost irrelevant.

The methods of Bland and Altman [9] were used to investigate the repeatability and agreement of the two methods.

3 Results

The results of the comparison can be seen in table 1, where the active ellipse method shows greater repeatability. However there is considerable agreement between the two methods, allowing for confidence in the results returned by our method.

Technique	**Repeatability Coefficient (mm)**
Manual Annotation	1.70
Active Ellipse	1.35

Table 1. Repeatability coefficients for manual and automatically placed ellipses

Limits of agreement between the manual annotator and the system are -0.42mm to 0.47mm (see Fig 4) meaning that this system could replace the manual annotator with confidence.

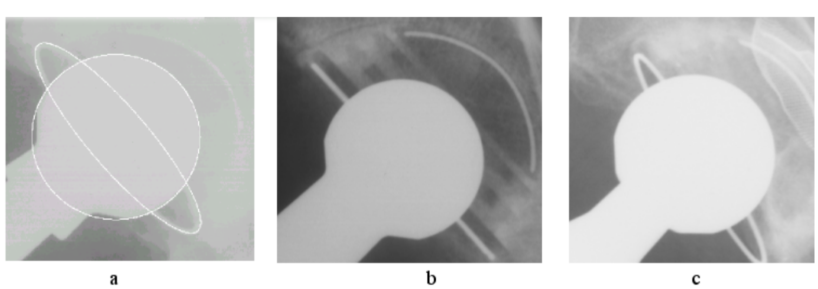

Figure 3. a) Successful location of the femoral head and the acetabular rim. b) Radiograph where the acetabular rim is non-elliptical. c) Elongated elliptical acetabular rim where method currently breaks down.

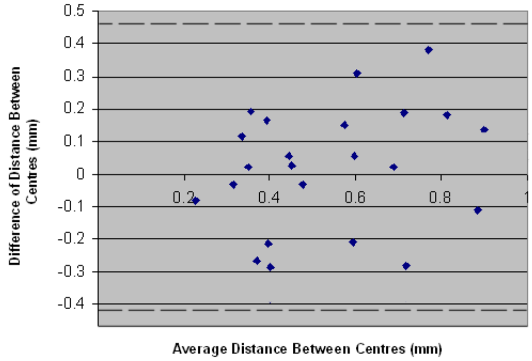

Figure 4. Scatter plot showing agreement between the manual annotator and the active ellipses measurements

4 Discussion

The results show the technique of active ellipses to be one worthy of attention, and are able to measure the wear of similar data in a clinical situation. With the robust LMedS ellipse fitting method it is also believed the system should be able to cope with deformities of the wire marker whilst maintaining an elliptical shape.

The method breaks down when confronted with particularly elongated ellipses in the rim (see Fig 3c), and in cases where there are no wire markers in the rim. However to extend the method to a different model or configuration (such as those presented by Hatfield) it would be necessary to build different models.

Planned experiments include use in a clinical study of wear, comparison with other methods (such as RSA) and the effect on the repeatability of decreasing the convergence criteria decided upon in Experimental Preparation and to improvement of the LMedS fit. Lastly the breakdown of the system for the 2 additional examples with eccentric rims it is believed that using a geometric ellipse fit, as opposed to the less accurate algebraic fit currently used will fix this. In cases where the rim manifests itself as a single straight line an alternative technique is needed to find the line instead of an ellipse, although it should be possible to build models to locate the edge of plastic or metal-backed rims without wire marking.

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