Image Analysis for Computer-Assisted Surgery of Hip Fractures

T. O. Ozanian[1], R. Phillips, W. J. Viant, A. M. M. A. Mohsen
Department of Computer Science, University of Hull, Hull HU6 7RX

Abstract. This paper focuses on the task of automatic feature detection for computer-assisted fixation of hip fractures. The features of interest are the lateral cortex line, the femoral neck centre and the femoral head centre, the latter being the most challenging of all. A nonconventional “divide-and-conquer” knowledge-based approach produces more reliable and faster results than the standard global image processing routine.

1. Introduction

Fractures at the neck of the femur, also referred to as hip fractures, are one of the most common orthopaedic fractures. The treatment involves a fixation by the use of a screw and plate combination (Figure 1). A variety of internal fixation devices exist but the surgical process is similar. The screw must be positioned accurately so that it passes through the neck, taps into the femoral head and terminates at a fixed distance from the hip joint surface. The margin for error is small as only a comparatively small region of cortical bone is available to accept the screw.

The fixation of hip fractures is among the procedures using a basic principle in orthopaedic surgery, namely "*the placement of an object (guide wire, screw, tube, scope etc.) at a specific site within a region, via a trajectory which is planned from one or more imaging modalities and governed by 3D anatomical constraints*" [1]. To implement this principle the surgeon needs to plan, execute, reappraise and modify a trajectory. Currently, the accuracy and safety of the procedures adhering to this principle depend on the surgeon’s judgement, experience, ability to integrate images, use of intra-operative x-ray, knowledge of anatomical and biomechanical constraints and eye-hand dexterity. The Computer Assisted Orthopaedic Surgical System (CAOSS), developed as a joint venture between University of Hull and Hull Royal Infirmary, aims to improve the planning and implementation of selected procedures where the basic orthopaedic principle holds [2]. This is achieved by providing the surgeon with an improved intra-operative imaging system based on a C-arm fluoroscopic image intensifier and a more precise means of carrying out the surgery using a position sensed drill. CAOSS converts the qualitative diagnostic image intensifier (a standard vision system for numerous orthopaedic procedures providing 2D fluoroscopic images) into a quantitative surgical trajectory guidance system to form part of the orthopaedic surgeon’s tools for implementing the basic orthopaedic principle. The perceived advantages of the new system are reduction of operation time, radiation exposure to staff and patients, tissue damage, and technical failure rate due to inexperience and complexity of implant positioning.

The planning of the trajectory by the system requires the identification of the favourable biomechanical position and understanding of the relevant hip anatomy. Normally, the guide wire should be placed centrally within the femoral head and neck on both anteroposterior (AP) and lateral views. The analysis of the problem has revealed the need for identification of three features from the two approximately orthogonal views. These are: 1) the midpoint of the narrowest diameter of the neck, i.e. the neck centre or the midcervical centre, 2) the midpoint of the largest diameter of the femoral head, or the head centre and 3) the lateral cortex of the femur shaft. A 3D reconstruction of these three features is obtained from the intersecting of projection planes and lines defined by the x-ray source and the appropriate feature in the 2D images. The ideal trajectory for the implant is considered to be the one that passes through point 1) and 2) and forms an angle of 135° with the lateral cortex (Figure 2). Normally, such a trajectory does not exist and different approaches are considered for obtaining the best approximation.

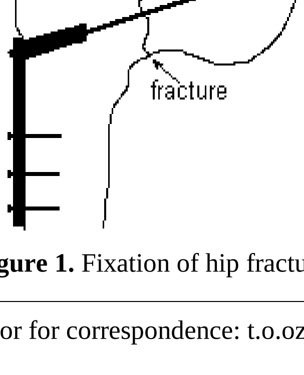

Figure 1. Fixation of hip fractures.

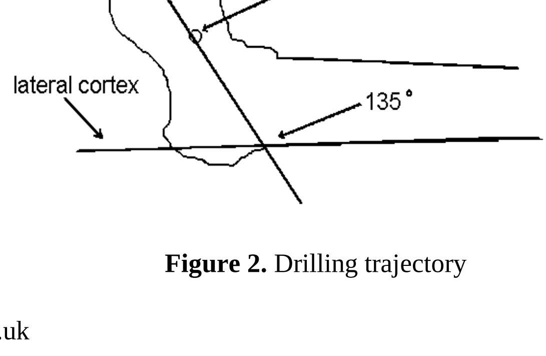

Figure 2. Drilling trajectory

[1] Author for correspondence: t.o.ozanian@dcs.hull.ac.uk

This paper presents the image analysis involved into automatic localisation of the features of interest for computer-assisted trajectory planning for internal fixation of hip fractures in orthopaedics and is a continuation of a work reported at a previous MIUA meeting [3]. Since the object is known, the detection process is regarded as a localisation task rather than a recognition one. Simple knowledge is used to facilitate the extraction. Major requirements for this system part are reliability and ability to provide the results in real time during surgery.

2. Method

Problem analysis reveals that all three features of interest are either part of the proximal femoral boundary or can be derived from its parts. Specific characteristics related to the acquired fluoroscopic images are poor bone vs. tissue contrast, poor signal-to-noise ratio, bone overlapping (the femoral head overlaps the pelvis), appearance of shadows, non-optimum exposure of the images (there is a trade-off between image clarity and radiation). As a result boundaries are often diffuse, obscured by other bony, fibrous or vascular tissue or shadows, shallow (i.e. there is just a small rise in optical density), with varying characteristics along their length and from patient to patient, false or ill-defined. All this strongly questions the success of the application of any of the standard techniques for image segmentation. The analysis of the problem shows that more reliable and fast results can be obtained if one can detect edges using properties of objects, rather than properties of edges per se. That implies the use of a priori knowledge about the problem domain.

Since a global approach is likely either to fail or substantially slow the feature extraction process, it was thought that a "divide-and-conquer" strategy is likely to improve the reliability as well as the computational cost of the segmentation process. The idea behind this strategy is the following. If an initial rough localisation for the femoral neck, shaft and head can be obtained, that is a region of interest (a bounding rectangle) is devised for each of the three features of interest, the result will be a separate substantially constrained search space for a particular feature. Furthermore, geometric relationships can be used to verify the plausibility of the results. This creates two additional benefits. First, if adequate results are not achieved at this stage, the entire procedure can be aborted without further expensive and unproductive processing. Second, if one distinctive feature is extracted first, then the knowledge of the geometric relationship between this feature and the rest can be exploited to guide the extraction of the rest (similar reflections have been found in the work of Efford [4]). For example, the localisation of the neck centre can facilitate the extraction of the lateral cortex line and the head centre (Figure 3).

Analysis of 1D grey level profiles has been chosen as a main segmentation tool to carry out the above strategy. Their use is adequate either when the objects of interest are round or when the nature and approximate orientation of the objects of interest are known in advance [4, 5]. In this work the use of profiles includes analysis of single local profiles as well as comparisons between consecutive profiles to estimate the approximate location of a certain event within an image.

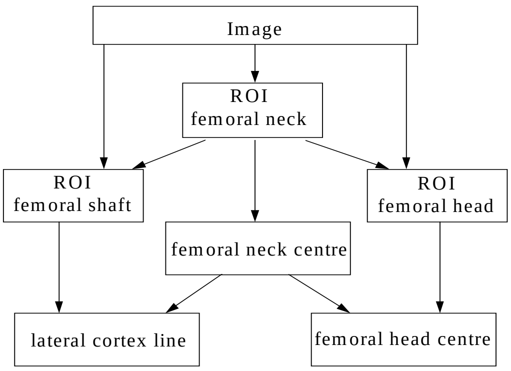

Figure 3. General strategy

2.1. Automatic Region of Interest (ROI) Determination

Regions of interest are determined by analysing local vertical and horizontal profiles. The main knowledge used here is that in both AP and lateral views the femoral neck orientation does not deviate substantially from the horizontal image orientation. Abrupt changes in vertical/horizontal profiles summed over adjacent columns/rows, taken at a fixed interval, show the location of the rectangular neck region. The location of the other regions is devised from the neck region. The processing is remarkably fast since only a limited number of profiles (about 20) are processed. Reliability is achieved by checking that the analysis of the orthogonal profile is non-contradictory. In fact, the results are checked for consistency on several occasions. Only very heavy shadows might distort or invalidate the output. In such a case a failure is reported, so that either features are marked manually (if possible) or a new x-ray shot is provided. Hence, poor images that are not worth further processing can be rejected at an early stage. Figure 4 demonstrates a real image taken during surgery with detected ROIs framed in white.

2.2. Neck Centre Detection

Knowing the approximate location of the femoral neck, a fast and simple procedure for automatic neck centre detection is applied. First, two sequences of points with a high horizontal gradient are found and assigned as belonging to the top and bottom neck boundaries. Then, for each candidate boundary point a confidence value is calculated based on connectivity with neighbouring points. Points with low confidence value are treated as erroneous and a correction procedure is devised which looks for new boundary points in the vicinity of the nearby points with high confidence value. Confidence values are updated after the correction. Finally, the minimal distance line between the two boundaries as well as the neck centre line are obtained by algorithms tolerating incomplete neck-boundary recovery (only points with high confidence value are considered). The intersection between these two lines gives the neck centre (Figure 4). Since the neck centre detection is leading the subsequent feature detection, strong validation of results is carried out during this stage of the processing, so that failures are caught and reported at an early stage.

2.3. Head Centre Detection

By and large, the head centre detection is the most challenging part of the automatic feature detection. The head centre can be derived if the boundary of the head is determined. However, a major problem is the particularly poor contrast around the femoral head in both views (AP and lateral) due to its overlapping with the pelvis. The effect is such that noise can be stronger then the signal at the boundary of the femoral head. The existence of shadows can create additional difficulties further deteriorating the contrast and causing the appearance of false structures. Another major problem is the partial appearance of a parallel running “boundary” (thick shadow) of the acetabulum. In fact, the acetabulum boundary has stronger signal than the femoral head boundary. Evidently, any attempts for recovery of the femoral head boundary based on classical gradient calculation are doomed to fail in this part of the x-ray image.

A way of solving the head centre detection problem is to gain enough points presumably belonging to the head outline, so that a fit to an analytic curve (ellipse) can be performed preferably tolerating outliers. Using this approach two questions arise which are interrelated to a certain aspect: 1) how to obtain a set of points that contain enough representatives truly belonging to the head outline; 2) how to design a quick, yet reliable ellipse fitting procedure.

Rule-based search for boundary points of the femoral head is performed as described below. Candidate boundary points are derived after examination of vertical profiles. Two sets of boundary points, namely one for the top part and one for the bottom part of the boundary, are obtained in the following way. A sliding t-test is applied to each vertical profile. Significant turning points in the result of the t-test reveal probable edges [5]. To restrict ambiguities the search is carried out within predicted narrow intervals for the top and the bottom of the head boundary. Initially the intervals are set around the last two high-confidence points of the top and bottom neck boundary. Then the intervals are moved up or down in a flexible way depending on the current state of the boundary (expanding, flat or shrinking) and the position of the points found within the previous interval. The role of this moving interval is to form a flexible template, which significantly restricts the number of outliers, yet is able to adjust its size and shape according to the temporary results. Other ways of discarding outliers are defined in the form of rules checking relations between neighbouring candidate boundary points. For example, there is a requirement that a candidate boundary point should form a smooth monotonous curve with neighbouring points. Consequently, points that violate this rule are discarded as outliers.

To derive the femoral head centre an ellipse fitting routine was developed similar to the one suggested by Rosin [6]. It is a robust technique based on accumulating many five-point ellipse fits to subsamples of the data and selecting the median of each parameter. A number of random samples of five points are drawn. To achieve higher stability and efficiency the random selection is designed so that there will be at least two points from the top and bottom boundary parts and these points are not close to each other. For each subsample the conic parameters are computed. Non-elliptic five point fits are rejected. The x and y coordinates of the ellipses' centres are accumulated separately. The femoral centre is estimated by taking the medians of the two accumulators. Results are shown on the test image in Figure 4.

2.4. Lateral Cortex Line Detection

The localisation of the lateral cortex line follows the procedure of first finding a sufficient number of boundary points belonging to the shaft and then fitting a line through them. In an AP view the shaft is sloped and the search of boundary points is further constrained by "squeezing" the region of the shaft by lines passing through the neck centre and two other characteristic points (point #1 and point #2 as shown on the test image in Figure 4). The latter points are automatically located by analysing the shape of horizontal profiles taken at some interval. Boundary points are gathered from high responses of applying a special mask designed to detect light-to-dark transitions with the appropriate orientation. In a lateral view the shaft is nearly horizontal in the image which is used to facilitate the search for boundary points.

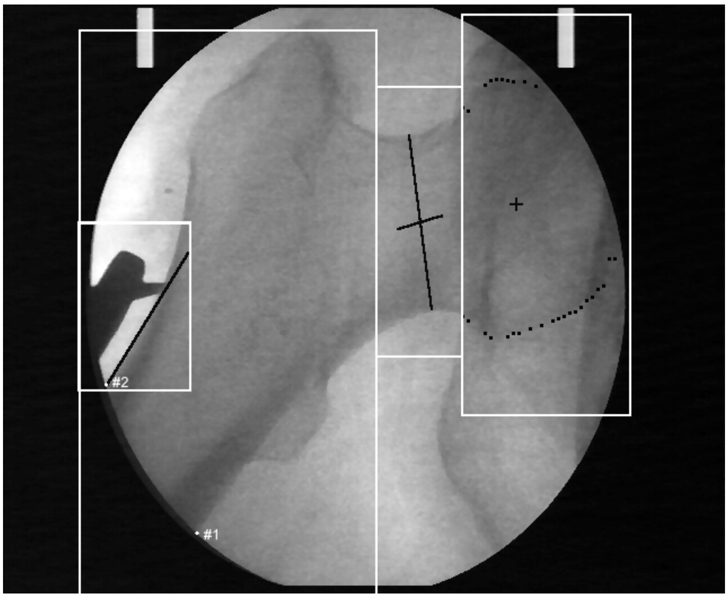

Figure 4. Automatic feature detection in AP view

3. Summary

The presented work addresses knowledge-based automatic feature detection for intra-operative surgery planning for internal fixation of hip fractures in orthopaedics. It is part of a joint large project between orthopaedic surgeons and engineers which aims to provide the surgeon with an improved intra-operative imaging system and a more precise way of carrying out specific orthopaedic procedures. The previous implementation of a prototype system involved manual identification of the geometric features which guide the planning of the drilling trajectory. However, this requires involvement of staff, hence, subjectivity and time taken in the operating theatre. The image analysis aims at further improving the overall system performance by providing alternative reliable and fast automatic localisation of the features of interest and is likely to achieve wide acceptance by operating theatre staff. The whole system has undergone pre-clinical trials and is now under validation prior to its introduction for clinical use. Future work concerning the automatic feature detection involves rigorous testing and further improving the reliability of the detection process.

Acknowledgements

The CAOSS project is supported by grants from the following funding bodies: the Hull Royal Infirmary, the University of Hull, the British Orthopaedic Association, the MedLINK.

References

1. A. Mohsen. *A non-invasive intelligent orthopaedic guide: concepts, issues, and efficacy assessment*. PhD Thesis, University of Hull, 1995
2. R. Phillips, W. Viant, A. Mohsen et al., "Image guided orthopaedic surgery: design and analysis", *Transactions of the Institute of Measurement and Control*, vol. 17:5, pp. 251-265, 1995
3. T. Ozanian, R. Phillips, W. Viant, A. Mohsen et al. "Automatic feature detection in x-ray images for planning a drilling trajectory in orthopaedic surgery", In *Proc. of Medical Image Understanding and Analysis* MIUA'97, Oxford, pp. 113-116, 1997
4. N. Efford. "Knowledge-based segmentation and feature analysis of hand-wrist radiographs", *Technical Report 94.31*, School of Computer Studies, University of Leeds, 1994
5. P. Souza. "Automatic rib detection in chest radiographs", *Computer Vision Graphics and Image Processing*, vol. 23, pp. 129-161, 1983
6. P. Rosin. "Ellipse fitting by accumulating five-point fits", *Pattern Recognition Letters*, vol. 14, pp. 661-669, 1993