Computer-Aided Image-Guided Bone Fracture Surgery: Concept and Implementation

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This paper describes the FRACAS computer-integrated orthopaedic system for assisting surgeons in closed long bone fracture reduction. FRACAS' goals are to reduce the surgeon's cumulative exposure to radiation and improve the positioning accuracy by replacing uncorrelated static fluoroscopic images with a "virtual reality" display of 3D bone models created from preoperative CT and tracked intraoperatively in real-time. Fluoroscopic images are used to register the bone models to the intraoperative situation and to verify that the registration is maintained. This paper describes the system concept, the software prototypes of the modeling, preoperative planning, visualization, and fluoroscopic image processing modules, and preliminary experimental results.

1. INTRODUCTION

Fluoroscopy-based orthopaedic procedures crucially depend on the ability of the surgeon to mentally recreate the spatio-temporal intraoperative situation from uncorrelated, two-dimensional X-ray images. Significant skill, time, and frequent use of the fluoroscope are required, leading to positioning errors and complications, and to significant cumulative radiation exposure of the surgeon [8]. Recent research shows that computer-aided systems can significantly improve the accuracy of orthopaedic procedures by replacing fluoroscopic guidance with interactive display of three-dimensional (3D) bone models created from preoperative CT studies and tracked in real-time. Examples include systems for acetabular cup placement [10] and pedicle screw insertion [5,6].

We are currently developing a computer-integrated orthopaedic system, called FRACAS, for closed medullary nailing of long bone fractures. Medullary nailing is a very frequent routine procedure that restores the integrity of the fractured bone by means of a nail inserted in the medullary canal [1]. The nail is placed without surgically exposing the fracture through an opening close to the tronchanteric fossa in the proximal femoral bone. The surgeon manually aligns the bone fragments, inserts a guide wire, enlarges the canal if necessary, and drives in the nail with a hammer. Lateral screws through the bone and

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nail are then inserted to prevent fragment rotation and bone shortening. All these steps are performed under fluoroscopic guidance.

FRACAS' goals are to reduce the surgeon's cumulative exposure to radiation and improve the positioning and navigation accuracy by replacing uncorrelated static fluoroscopic images with a "virtual reality" display of 3D bone models created from preoperative CT and tracked intraoperatively in real-time. Fluoroscopic images are used for registration – to establish a common reference frame – between the bone models and the intraoperative situation, and to verify that the registration is maintained. This paper describes the system concept, the software prototypes of the modeling, preoperative planning, visualization, and fluoroscopic image processing modules, and preliminary experimental results [9,13].

2. PREVIOUS WORK AND MOTIVATION

Two computer-based systems for long bone fracture reduction [7,12] and [4] focus on distal screw locking. Both use intraoperative fluoroscopy and optical tracking without preoperative CT images. [7,12] uses a passive mechanical arm with optical encoders to guide the surgeon to the right drilling position. It automatically identifies the distal holes in the fluoroscopic images, plans the drilling trajectory, and constraints the motions of the passive arm. [4] continuously displays the projection of the surgical tools as they move on preselected fluoroscopic images, thus approximating continuous fluoroscopy. Since the images are correlated, the surgeon can simultaneously view the tool's progression from several viewpoints. This is similar to the conventional procedure and reduces the number of images needed. However, it does not provide preoperative planning support, does not display spatial views, and does not update the bone fragment positions in real time.

FRACAS aims at assisting the surgeon in all the steps of fracture reduction, not just in distal locking. It provides 3D bone modeling, preoperative planning, image processing, and anatomy-based registration with fluoroscopic images (under development). We believe that the additional cost and time of the preoperative CT study is outweighed by the potential reduction in more expensive intraoperative time, in minimizing mistakes and repetitive attempts at fracture reduction, and in reducing the surgeon's exposure to radiation. CT is usually readily available for trauma patients, which are likely to have other CT studies done anyhow, adding little preoperative time and morbidity.

3. SYSTEM AND PROTOCOL DESCRIPTION

The FRACAS system consists of a standard C-arm, a tracking unit (aka OPTOTRACK^{TM}), and a computer workstation with custom software. The C-arm is used to capture fluoroscopic images to register the preoperative bone fragment models and the intraoperative bone position. The tracking unit is used to provide accurate, real-time spatial object positions with three cameras following infrared light-emitting diodes (LEDs) rigidly mounted on the surgical instruments or attached to the bones via bone screws. The images and the tracking data are transfered to the workstation via a video frame grabber and a serial port. The computer workstation is used preoperatively for modeling and planning, and intraoperatively for data fusion and display.

The procedure protocol starts with the acquisition of a preoperative CT study of the healthy and fractured bones. Surface and canal bone models are then constructed by the modeling module. Using the planning module, the surgeon interactively selects the distal and proximal bone fragments and nail type, length, and diameter. Shortly before the surgery, the C-arm and the tracking unit are calibrated by a technician. The surgeon prepares and exposes the patient's femur head following the usual procedure. To track the position of the bone fragments, the surgeon rigidly implants two specially prepared bone screws with LEDs attached to them. Fluoroscopic images are then captured without the nearby presence of the surgeon to perform the registration with the preoperative bone fragment models. With the LEDs in place, the tracking is activated, following in real time the location of the bone fragments and surgical instruments. The visualization module displays the virtual reality image with the bone fragments and surgical instrument models in their current position. The surgeon manipulates the bone fragments and surgical tools, following their relative positions and orientations on the monitor until the desired result is obtained. A new set of fluoroscopic images is captured and registered to confirm the match between the intraoperative situation and the displayed model. This process is repeated during the subsequent steps of the procedure.

3.1. Modeling

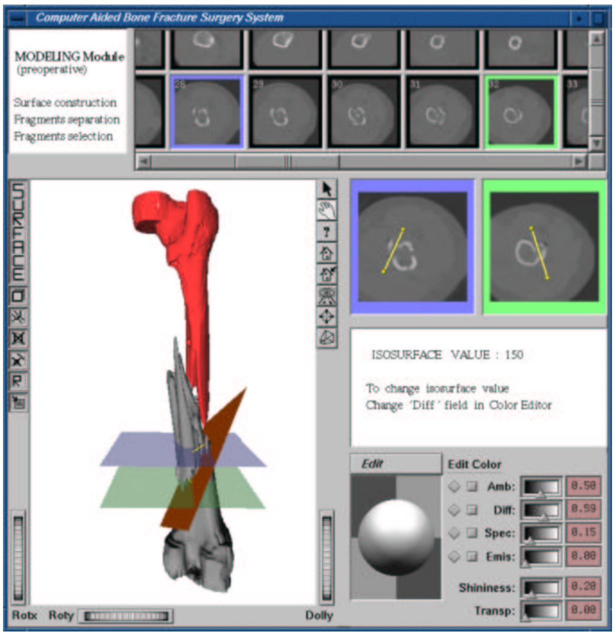
The modeling module inputs the CT data and a user-defined bone density threshold value, and outputs inner and outer surface models of selected proximal and distal bone fragments. The models are produced by first creating polygonal surface models of the bone external and internal fragment surfaces with an extended Marching Cubes algorithm. This usually lumps together bone fragments that are in contact due to the action of the muscles, producing a single connected piece for linear fractures or several pieces for segmental and comminuted fractures. Since threshold information by itself is not sufficient to determine when a new fragment begins and when one ends, the surgeon interactively defines the extent of the fragments of interest with cutting planes whose intersection define regions of interest. Figure 1 shows the modeling module window with a segmental comminuted fracture of a 44 slice CT set taken at 10mm, yielding models of about 75,000 triangles.

3.2. Nail selection

The nail selection module assists the surgeon in determining the optimal nail type, size and length when a CT of the healthy bone is available. To choose a nail, the surgeon interactively performs diameter and height measurements on the CT slices and on the reconstructed 3D bone model. Having determined the closest standard diameter and nail length, the system retrieves and displays the corresponding nail from a predefined CAD library of nail models available at the site. The surgeon can then interactively position the nail in its inserted position and verify that it fits in the canal and that there is no impingement with the knee or hip joints. Although the actual nail bends when it is inserted into the canal, the displayed nail position is close enough for the evaluation.

3.3. Visualization

The visualization module provides the surgeon with a virtual reality view of the intraoperative position and orientation of the proximal and distal fragments, the nail, and the surgical instruments. The positions are updated with real-time data from the tracking unit, after the preoperative model and the intraoperative situation have been registered (Figure 2). The system displays the central part of the exterior bone fragments translucid



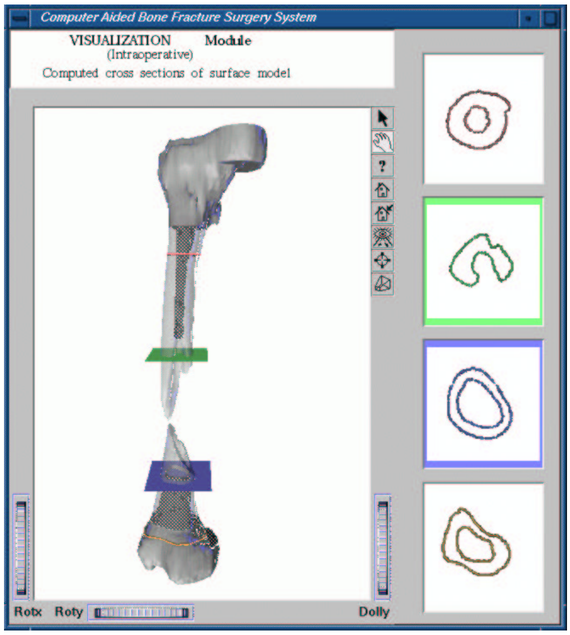


Figure 1. The modeling module, showing the CT slices (top window), the fractured bone surface model (left bottom window), and the detail of the selected CT slices (horizontal planes) used to define the cutting plane (slanted) separating the bone fragments.

Figure 2. The Visualization module display, showing the proximal and distal bone fragment models, the planes of four selected cross-sections, and the inner and outer bone contours (four left windows)

and highlights the canal surface inside. The femoral head and the condyles are displayed opaque to provide a reference frame for the joint and bone axes.

3.4. Fluoroscopic image processing

To use fluoroscopic images for anatomy-based registration, it is necessary to correct them for distortion, obtain the camera parameters, and extract the bone contours to be matched with projections of the 3D bone fragment models. The main difficulties are that the images are noisy, have limited resolution, exhibit non-uniform exposure variation across the field of view, and have varying contrast and exposure from shot to shot. While many methods for image distortion correction, camera calibration, and contour extraction are described in the literature, our method focuses on fluoroscopic bone images emphasizes integration, full automation, simplicity, robustness, and practicality.

For distortion correction, we compute a local dewarp map by imaging an aluminum alloy plate with 405 uniformly distributed 4mm diameter holes machined to 0.02mm precision. The map is obtained by bilinearly correlating the geometric and image center coordinates of the hole centers. For camera parameter calibration, we use Tsai's eleven parameter pinhole camera model and follow his two-step solution method. The parameter values are obtained by comparing the geometric and image center coordinates of 18 5mm steel balls arranged in three parallel planes and angularly distributed to avoid overlap in the image mounted on a three-step hollow cylindrical Delrin^{TM} calibration object. Our

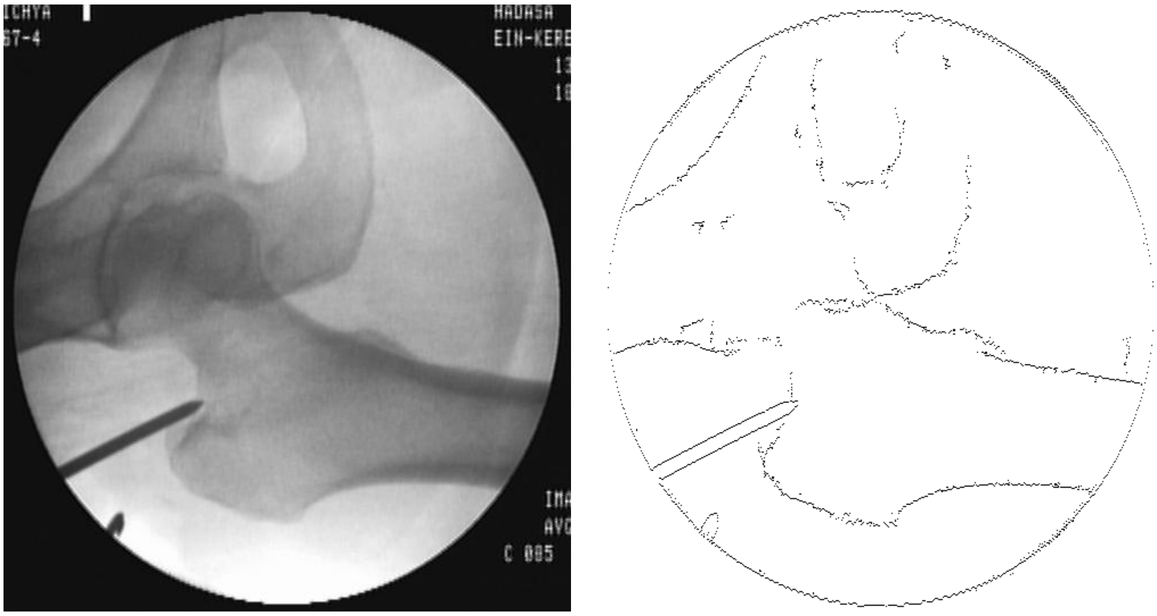


Figure 3. Original fluoroscopic image (left) and after contour extraction (right).

experimental results show an average dewarping accuracy of 0.1mm and always below 0.2mm, and average calibration error of 0.2mm and always below 0.45mm. We found significant dependence on the C-arm orientation, with dewarp variations of up to 1mm for angles of 10°. We thus acquire dewarping maps and camera parameters at several preselected C-arm orientations, e.g., anterior-posterior and lateral.

To reliably extract bone contours from fluoroscopic images, we developed a new bone contour segmentation algorithm based on robust image region statistics computation [2]. Working on the gradient image, the algorithm starts by computing a global threshold and then performs region growing based on adaptive local thresholds and zero-crossings filtering. Because the algorithm uses both global and local thresholds, it is less sensitive to the exposure variations across the field of view. Pixels are classified into one of three categories, *bone*, *candidate*, or *background*, according to the number of pixels above a predefined percentile, and not according to a prespecified absolute value. The percentile indicates the number of pixels in the gradient image histogram with gray values below (background) or above (bone), with candidate pixels in between. Initial region classification is obtained with global percentile thresholds. To overcome the non-uniform exposure, the classification is adaptively updated with local percentile thresholds over a fixed size window. Filtering the result with the original image zero crossings localizes the contour inside the region. Figure 3 shows typical results from an actual surgery.

4. CURRENT AND FUTURE WORK

Our current work focuses on registering the extracted bone contours with surface bone models obtained from preoperative CT images [3]. Our experiments suggest that after dewarping and calibration, submillimetric spatial positioning accuracy, possibly better than 0.5mm, is achievable with standard equipment. Preliminary contour segmentation results show good contour tracing with very few outliers. These can be removed with a simple model-based scheme or by combining segmentation and registration [3]. Near term plans include the integration of real-time tracking, and in-vitro prototype testing.

REFERENCES

1. Brumback R.J., "The Rationales of Interlocking Nailing of the Femur, Tibia, and Humerus" *Clinical Orthopaedics and Related Research*, **324**, 1996.
2. Garza-Jinich, M., Meer P., Medina, V., "Robust Retrieval of 3D Structures from Magnetic Resonance Images" *Proc. of the Conf. on Pattern Recognition*, Austria, 1996.
3. Hamadeh, A., Sautot, P., Lavallée, S., Cinquin, P. "Towards Automatic Registration Between CT and X-ray Images: Cooperation Between 3D/2D registration and 2D Edge Detection", *Proc. 2nd Int. Symp. on Medical Robotics and Computer Assisted Surgery*, Baltimore, 1995.
4. Hofstetter, R., Slomczykowski, M. Bourquin, I, Nolte, L.P, "Fluoroscopy Based Surgical Nagivation – Concept and Clinical Applications", *Proc. 11th Int. Symposium on Computer Assisted Radiology and Surgery*, H.U. Lemke, et al. eds, 1997.
5. Lavallée, S., Sautot, P., Troccaz, J., Cinquin, P., Merloz, P. "Computer Assisted Spine Surgery: a Technique for Accurate Transpedicular Screw Fixation Using CT Data and a 3D Optical Localizer", *J. of Image-Guided Surgery* 1(1), 1995.
6. Li Q.H., Holdener H.J., Zamorano L., King P., Jiang Z., Vinas F.C., Nolte L.P., Visarius H., and Diaz F., "Computer-Assisted Transpedicular Screw Insertion" *Lecture Notes in Computer Science*, Springer, 1996.
7. Phillips R., Viant W.J., Mohsen A.M.M.A., Griffits J.G., Bell M.A., Cain T.J., Sherman K.P. and Karpinski M.R.K., "Image Guided Orthopaedic Surgery - Design and Analysis" *IEEE Transactions on Robotics and Control*, March 1996.
8. Sanders R. *et. al*, "Exposure of the Orthopaedic Surgeon to Radiation", *J. of Bone Joint Surgery* 75 A(3), 1993.
9. Tockus, L. "A System for Computer-Aided Image-Guided Bone Fracture Surgery: Modeling, Visualization, and Preoperative Planning", Msc Thesis, Hebrew U., Jerusalem, July 1997.
10. Simon, D.A, Jaramaz, B, Blackwell, M., Morgan, F., DiGioia, A.M., Kischell, E., Colgan, B., Kanade, T. "Development and Validation of a Navigational Guidance System for Acetabular Implant Placement", *Proc. of CVRMed-MRCAS'97*, Lecture Notes in Computer Science 1205, Troccaz et al. eds., Springer 1997.
11. Tsai, R., "A Versatile Camera Calibration Technique for High-Accuracy 3D Machine Vision Metrology Using Off-the-Shelf TV Cameras and Lenses" *IEEE Journal of Robotics and Automation*, Vol. RA-3, No. 4, August 1987.
12. Viant, W.J., Phillips, R., Griffiths, *et al.* "A Computer Assisted Orthopaedic System for Distal Locking of Intramedullary Nails", *Proc. of MediMEC'95*, Bristol, 1995.
13. Yaniv, Z., "Fluoroscopic Image Processing and Registration for Computer-Aided Orthopaedic Surgery". Msc Thesis, Hebrew U., Jerusalem, July 1998.