Computer Integrated Revision Total Hip Replacement Surgery: Preliminary Report

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Abstract

We describe an ongoing collaborative effort to develop a computer-integrated system to assist surgeons in revision total hip replacement surgery (RTHR). In RTHR surgery, a failing orthopaedic hip implant, typically cemented, is replaced with a new one by removing the old implant, removing the cement, and fitting a new implant into an enlarged canal broached in the femur. The goals of the project are the significant reduction of cement removal labor and time, the elimination of cortical wall penetration and femur fracture, the improved positioning and fit of the new implant resulting from precise, high quality canal milling, and the reduction of bone sacrificed to fit the new implant. Our starting points are ROBODOC *, a computer-integrated system for primary hip replacement surgery currently in clinical trials, and the manual RTHR surgical protocol. We first discuss the main difficulties of computer-integrated RTHR and identify key issues and possible solutions. We then describe a new system architecture for preoperative planning and intraoperative execution and propose an incremental development strategy to bring the system to the operating room. We conclude with a report of preliminary results in CT artifact removal, robot and image registration, planning with a spreadsheet of X-ray and CT images, interactive cement cut volume definition, and cement machining.*

Keywords: computer-assisted surgery, orthopaedics, revision total hip replacement, preoperative and intraoperative planning, image-based registration, ROBODOC™ system.

Introduction

This paper describes an ongoing collaborative effort to develop a computer-integrated system to assist surgeons in revision total hip replacement surgery (RTHR). In RTHR surgery, a failing orthopaedic hip implant, typically cemented, is replaced with a new one by removing the old implant, removing the cement, and fitting a new implant into an enlarged canal broached in the femur. As the installed base of orthopaedic implants grows and ages, replacement of existing implants, especially those relying on bone cement for fixation and fit, is steadily increasing. In 1992, 23,000 RTHR procedures were performed in the U.S., with an annual growth rate of 10%. The average cost per procedure was $23,774 with an average hospital stay of 10.9 days [1].

RTHR is a difficult procedure fraught with technical challenges and a high incidence of complications. Femoral cement removal and canal preparation present the most difficulties [4, 24]. The goal is to remove as much of the old cement as possible to facilitate the insertion of a new implant and provide an optimal surface for bone support and interdigitation. While the cement mantle in the proximal area of the canal is visible and easily accessible, the cement mantle and plug in the distal area are hard to see and reach due to the canal depth and the bowing of the femur. Removing cement is tedious, time-consuming, and risky, taking on average between 30 minutes and 2 hours. Femoral canal preparation is more difficult than in a primary case because there is little good bone left and because the surgical manipulations are more delicate. The reamers tend to follow the old canal, making axis and canal position corrections virtually impossible. The femur is fractured in about 18% of cases, and the surgeon breaks through the cortical wall of the femur in another 10% of cases [22]. When errors occur, more time is required to repair the damage, additional blood is lost, and the infection rate increases.

None of the current techniques for cement removal is fully satisfactory. Osteotomes and flexible reamers are difficult to manipulate and have the tendency to follow the old canal. Hand-held high speed drills cut cement fragments but require fluoroscopy for careful guidance to avoid perforating the femur walls. Lateral femoral windows facilitate distal access to the cement but compromise bone integrity. A recently developed method uses new low-viscosity cement that bonds to the old cement to form a plug. The plug is then pulled out by screwing in a threaded extraction rod and pulling out pieces in short segments. This technique cannot be used when the cement mantle widens distally or when cavities are present in the side of the bone. New technologies, such as cement softening using an ultrasonically driven tools or the use of the lithotripster to fracture cement, might lower the complication rate but are unlikely to significantly improve accuracy or shorten the procedure.

The growing numbers, greater difficulty, and reduced margin for error make RTHR a natural target for robotic machining to remove old cement and prepare the new cavity. Our goals are (1) elimination of cement removal complications, specifically cortical wall penetration and bone fracture, (2) significant reduction of cement removal labor and time required, (3) improved positioning accuracy and fit of the new implant resulting from precise, high quality canal milling, and (4) reduction of bone sacrificed to fit the new implant. In addition to the direct patient benefits, these advantages can save costs, both by reducing operating room charges (about $1500/hr) and by shortening hospital stay and recovery time.

Our starting points are ROBODOC™[19, 23], Integrated Surgical Systems' (ISS) computer-integrated system for primary hip replacement procedures, and the manual RTHR surgical protocol. ROBODOC was developed clinically by ISS from a prototype developed at IBM Research and is currently in clinical trials. Preclinical testing showed an order-of-magnitude improvement in precision and repeatability in preparing the implant cavity. About 65 human cases have been performed to date, with very encouraging preliminary results. In primary hip replacement (PTHR) procedures, the damaged joint connecting the hip and the femur is replaced by a metallic implant inserted into a canal broached in the femur. The ROBODOC system allows the surgeons to plan preoperatively the procedure by selecting and positioning an implant with respect to a CT study and mill the corresponding canal in the femur with a high speed tool controlled by a robotic arm intraoperatively.

The ROBODOC system consists of an interactive presurgical planning system, called ORTHODOC, and a robotic system for use in the operating room. ROBODOC PTHR starts with a minor surgical procedure in which three small pins are implanted in the femur. A CT scan of the patient shows the femur and the pins, which are used to register the images and the robot. Next, ORTHODOC processes the CT data set, locates the three pins within the CT data set, and allows the surgeon to select three orthogonal planar slices through the 3D image volume. The surgeon selects a desired implant model and size and interactively positions with a mouse a CAD model of the implant relative to the CT volumetric images. ORTHODOC generates cross-sectional displays of the implant model showing the planned placement superimposed upon the planar sectional views selected by the surgeon. In the operating room, surgery follows the established protocol up through the point where the femoral head is removed. The femur is then placed into a fixation device attached to the robot's base. The three pins are exposed and located in robot coordinates by a combination of force-compliant guiding and autonomous tactile search by the robot. The system then computes the transformation from CT (planning) to robot (actual) coordinates and machines out the desired shape in the femur while the surgeon follows the progress on an intraoperative display. Once the shape is cut, the robot is moved out of the way and the procedure resumes manually as usual.

RTHR is more complex than PTHR: it requires more system capabilities and has more uncertainty associated with it. Surgeons must plan for and remove the old implant and the old cement before cutting the new canal cavity. They must plan for the new cavity in the presence of the old implant and cement. They must forsee complications in implant and cement removal, which might change or invalidate the preoperative plan. Consequently, computer-assisted RTHR surgery requires substantial extensions and modifications to the ROBODOC PTHR paradigm. To summarize, the system must provide, in addition to the current capabilities, cement removal planning and cutting capabilities, intraoperative plan modification and uncertainty assessment, possibly with the integration of intraoperative fluoroscopic images with preoperative CT data. Two key difficulties are (1) the lower quality of the CT images due to artifacts produced by metallic implants and (2) the registration of the images, the plan, and the robot to the femur.

In the rest of this paper, we discuss the main difficulties of computer-integrated RTHR, identify the key technical challenges, and investigate possible solutions. Based on these observations, we develop a new system for preoperative planning and intraoperative execution and propose an incremental development strategy to bring the system to the operating room. We conclude with preliminary results on CT artifact removal, robot and image registration, planning with a spreadsheet of X-ray and CT images, interactive cement cut volume definition, and cement machining.

Computer-integrated RTHR: requirements

To identify the requirements of computer-integrated RTHR surgery, we follow the steps of the manual RTHR procedure with the Robodoc PTHR protocol. We identify the differences, missing components, and assess the adequacy of the current techniques. We evaluate the relative importance of the difficulties that arise and propose possible solutions to them. The purpose is to gain an understanding of the practical problems and systematically explore alternative solutions.

Problem assessment

CT images

X-ray CT images of body sections containing metal objects are often corrupted by streaks that radiate from the regions of the image where metal is present (Figure 1). Because metal objects are opaque to X-ray beams in the diagnostic energy range, their scannings yields incomplete projection data. CT images reconstructed from this incomplete data contain artifacts, whose extent depends on the material type and volume of the implant. Artifacts in CT scans of RTHR patients with metal femoral implants are most marked in the proximal section, where the implant is the thickest. The artifacts make it difficult to determine the boundary between the implant, the cement, and the bone. Since the quality of the CT images is key in determining the quality of the surgical plan, reducing artifact as much as possible is essential.

Preoperative planning

Preoperative planning of RTHR surgery involves two steps: cement removal and new implant planning. Cement removal planning defines the cut volume that will remove as much of the old cement as possible. New implant planning determines the type, size, and position of the new implant and the associated canal cut volume that guarantees a precise fit. Cement removal and new implant planning are interrelated, since the bone stock left after cement removal determines the implant types, sizes, and positions that can be used. Conversely, the available implant types and sizes determine the new canal shapes, which indicate what bone and cement volumes should be removed and what contacts and gaps will appear when the new implant is inserted into the canal. The main difficulties of RHTR preoperative planning are:

- determining the precise extent of the cement mantle and the bone stock from CT data requires substantial experience and judgement from the surgeon. The boundary between cement and bone is often unclear, since cement tends to partially fill porous bone, creating heterogeneous zones that must be evaluated individually. In addition, CT image artifacts introduce further uncertainty whose extent must be quantified.

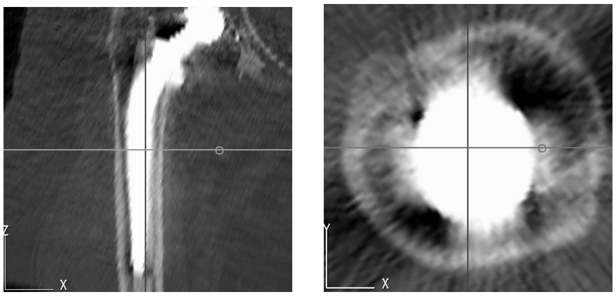

Figure 1: Frontal and cross sectional ORTHODOC views of a CT study of a failing implant.

- defining the cement cut volume. While the cut shape for the new implant is determined by the type and size of the implant chosen, the cement cut volume varies for each individual case and must be defined by the surgeon. A fast, convenient, and accurate method must be developed to define 3D cut volumes from CT data.
- identifying and correcting discrepancies between the cement cut volume and the canal cut volume. Ideally, the canal cut volume must minimally include the cement cut volume to preserve as much good bone as possible and avoid contact gaps when the new implant is in place. While some surgeons would leave small volumes of old cement in non-critical areas or use bone graft to fill in cavities to achieve a tight fit, a more rigorous analysis is required to determine the best trade-off.
- determining the shape and extent of the cement mantle and bone stock that will be left after the old implant is removed. In many cases the old implant is loose and can be removed without altering the cement mantle or bone stock. However, porous or coated implants can disrupt the areas of bone ingrowth, causing bone detachment or femoral fracture, thus invalidating the preoperative plan. The options are to intraoperatively modify the plan, to create alternative backup plans, or to complete the procedure manually.

Intraoperative validation and re-planning

To account for the uncertainties introduced by the old implant removal, preoperative plans must be compared and validated with the intraoperative situation. This validation was is not necessary for the PTHR Robodoc procedure since the femoral anatomy does not change before the canal is cut. It is necessary for RTHR, even when the old implant removal presents no complications, because the surgeon needs to gain confidence in the preoperative plan and possibly modify it with the additional intraoperative information. The modifications include changing the cement cut volume to account for more or less cement removal (depending on how much cement came out with the old implant), modifications to the shape of the cement cut volumes, and adjustments to the new implant size and positions.

The key difficulties are the integration of the intraoperative data with the preoperative plan and the modification of the preoperative plan. Currently available sources of intraoperative data are visual and tactile inspection and fluoroscopic C-arm images of the canal and remaining cement mantle. To be useful, this data must be integrated and correlated with the preoperative plan and CT study. Any modifications to the preoperative plan must be done quickly and accurately, since time is at premium in the operating room.

Image and robot registration

Robotic procedures require registering preoperative plans and images to the robot and to the actual anatomy. The Robodoc system for PTHR surgeries uses three pins implanted prior to surgery in the femur before the patient is scanned. Two pins are implanted into the condyles and one in the greater tronchanter. In RTHR surgeries, osteotomy of the greater tronchanter is often necessary to provide better exposure and ease the insertion of the new implant. Thus, a new location that does not interfere with the cutting tool or require more invasive surgery must be found. Alternative methods using external fiducials or pinless registration can replace the implanted pins altogether.

Cement and bone cutting

Once the leg has been fixated and the robotic arm has been registered, the cement and the canal are machined. A revision canal contains cement and is one-third to one-half longer than a primary canal, extending below the bow of the isthmus. Because of its extended length and curvature, machining the new canal raises issues of robot reachability and workspace capabilities, stiffness of the robotic arm and cutting tool, and accessibility for curved machining paths. Experiments must be carried out to determine the effects of cutting cement with high speed tools: stresses and femur fracture analysis, accuracy, rough vs. finish cutting passes. These will establish whether the Robodoc arm and cutting strategy must be significantly redesigned or not.

Key issues

We have identified four major issues that must be addressed to develop a practical RTHR surgery system:

- *preoperative planning under uncertainty:*
  Imaging artifacts, old implant removal, and cement removal introduce uncertainties in the selection and positioning of the new implant. Assessing their influence and importance is key to determining the need and importance of alternative preoperative imaging and intraoperative re-planning.
- *cement cut volume definition:*
  A custom cement cut volume must be created for each individual patient. The creation process must be fast, intuitive, and should produce an accurate, machinable shape. The cement cut shape must be compared with the implant cut shape to identify discrepancies, such as lack of surface support and pockets.
- *intraoperative plan validation and modification:*
  Higher confidence in the preoperative plan and the old implant removal procedure reduces the intraoperative planning requirements. It is essential to determine the nature and extent of intraoperative replanning and to establish what intraoperative data is necessary to perform it.
- *Image and robot registration:*
  Accurate registration of the preoperative and intraoperative images and plans with the robot and the femur is essential for adequate planning and execution. The imaging modalities, their resolution, the registration method, and the length of the registration chain, determine the maximum cumulative error. It is important to understand the contribution of each element to develop registration methods that are practical, robust, and fast.

Understanding and evaluating the importance and interrelationship of these issues is essential in designing an integrated system. In the next section, we consider each one of these issues and systematically explore possible solutions.

Computer-integrated RTHR: possible solutions

Preoperative planning under uncertainty

CT image artifact removal is a natural stating point for attempting to reduce the uncertainty associated with preoperative planning. Several approaches have been considered for reducing artifacts in CT images produced by metal objects. These include: (1) using implants made of materials with lower attenuation coefficients or with smaller cross-sectional areas [20]; (2) using higher energy X-rays beams that will not be blocked by the implants [20]; (3) averaging out the effect of the artifacts by multiplanar reformatting (interpolating and reslicing) of the 2D images stack [20]; (4) averaging out the effect of the artifacts by combining multiple image sets, each scanned with the gantry at a different angle [26]; (5) interpolating the missing projection data and reconstructing the images from these completed projections [6, 8, 13, 15, 16, 17, 18], and; (6) creating simulated projection data from the images, interpolating the missing data in these projections, and then reconstructing the images [25].

For reducing artifacts in CT images of RTHR patients, (1) is obviously not an option. The needs for limited patient dose and low energy to discriminate among materials (biological tissue types and synthetic material such as cement) rules out (2). The averaging effect of (3) reduces not only artifact but also image resolution, while (4) requires longer scanning time and higher patient exposure to radiation. In principle (5) can produce the best results, but in practice, access to raw projection data (and proprietary data formats) is problematic. (6) is the most practical option, which has the added advantage that any methods developed can readily be applied to real projection data when these are available.

Another way to improve the information available for preoperative planning is to capture and integrate information from an additional source such as images from digitized multi-planar film X-rays or from a fluoroscopic C-arm. Since there are no reconstruction artifacts in plane X-rays, the contour of the implant is clearly visible and the cement mantle is not occluded. To be useful, several 2D images must be captured and accurately registered to the CT study. This requires using internal or external fiducials for the registration, or developing anatomy-based 2D/3D registration techniques. A good alternative is to use one or more scout images taken with the CT scanner at the time of the study. The CT scanner provides the precise data for correlating the scouts with the CT data. Another possibility is to eliminate the CT data set altogether and rely only on co-registered X-ray images (a crude version of this is method is currently used to plan manual surgeries with acetate ovelays). The disadvantage is that much less volumetric data is available for planning, although it is inexpensive.

Using both X-ray images and CT data requires considering how to best present the information to the surgeon. The ORTHODOC system presents 3 orthogonal cross sections of the CT data set. However, the X-ray images are non-orthogonal projections from different perspectives. It remains to be determined how well the surgeon can position the implant and define a cement cut volume with these two kinds of images.

Cement cut volume definition

A custom cement cut volume must be created for each individual patient. The creation process must be fast, intuitive and produce an accurate, machinable shape. Cement cut volume definition can be approached in several ways. Cut volumes can be designed like custom implants: by specifying, for each CT slice, points defining a 2D contour bounded by splines. The stack of 2D slices defines a 3D cut volume. Adjusting the cut volume shape to fit the cement requires moving the points. While accurate, this method requires inputing many points, a forbidding task for the surgeon. An alternative is to define the contours in a subset of the slices and automatically interpolate the rest. This trades off number of input points for accuracy of matching shape. Another possibility is to have one or more simple, parameterized shapes, such as cones with elliptical cross-sections, and fit them to the cement by varying the parameters. Although modifying a few parameters is fast, this method is potentially unintuitive and inaccurate. A combination of both methods, which uses simple parameterized shapes for the rough fit and control point modification for fine tuning could provide the best trade-off.

The cut volume shape thus defined must then be approximated to a machinable shape, determined by the radius of the cutter and the machining axis. The smaller the cutter radius, the more accurate the shape, but the longer it takes to machine Multi-axis, adaptive machining methods, in which the cutter axis is repositioned during cutting allow tighter fits but require more complex computation.

Once the cut volume shape has been defined, the new implant and its associated canal must be selected and positioned. The implant can be selected and positioned manually, as currently done with the ORTHODOC system, or by interactively defining correspondences relating implant and image landmarks that should coincide. In the later approach, the surgeon can use the mouse to designate points on the implant that should align with points in individual X-ray and CT images. The system then computes an implant position and orientation that brings the selected pairs of points as close together as possible (by solving and formulating a least-squares minimization problem, achieving an optimal placement with respect to the specified correspondences). By interactively adding, deleting, and modifying correspondences, the surgeon can quickly find the best implant position. This method is potentially less time-consuming because it simultaneously reduces divergences on several individual views.

Comparing the cement cut shape and the positioned implant cut shape is necessary to identify discrepancies, such as lack of surface support and pockets. The comparison can be left to the surgeon, by graphically overlaying the two volumes and showing them in different views. Reconciling discrepancies between the two cut volumes can be difficult. An alternative strategy is to define a single cut volume for both the cement cut volume and the new canal cut shape. In this scheme, the new implant size and position is chosen so as to contain all or most of the cement and the old canal. The cut volume associated with the new implant is then used to mill the old cement mantle, cement plug, and new canal shape simultaneously. The advantage of this approach is that no new cut shape needs to be defined or modified. The disadvantage is that a trade-off must be made between removing all the old cement and removing too much good bone. Lumping old cement removal and new canal preparation assumes that the preoperative plan is of high quality, since no intra-operative adjustment is possible once the robot starts cutting the shape. Also, it diverges from current practice, which views cement removal and canal preparation as two distinct steps.

Intraoperative plan validation and modification

Fluoroscopic images provide the most practical alternative for intraoperative plan validation. Visual and tactile inspection rely on the surgeon's ability to mentally correlate the CT data to the intraoperative situation. This correlation, by its nature, qualitative, and can only detect major discrepancies. Fluoroscopic images provide more accurate data but must be dewarped and co-registered with the CT data to be useful in a robotic procedure. Other intraoperative imaging techniques, such as portable CT or ultrasound devices, are either not widely available or not sufficiently accurate.

The preoperative plan can be validated by superimposing the cut volume and the new implant projections on the new X-ray images. The surgeon can visually judge their adequacy and either proceed or modify the plan. One approach is to choose the best of several alternative preoperative plans. Alternatively, the surgeon can change the shape and size of the cut volumes using the same tools used in preoperative planning, although this can be cumbersome and time-consuming. It is best to first determine the extent of the discrepancies and the nature of the modifications required before committing to a specific solution.

Image and robot registration

Robot-to-patient and robot-to-image registration can be achieved with implanted fiducials, as in the current ROBODOC system, with external fiducials, or without fiducials. With external fiducials, a fixator with fiducials can be used to provide a base coordinate system. The intraoperative images can be registered to the X-ray fiducials, which will be registered to the robot by tactile search to locate the fixator. The patient's femur can then be located in the images, and the robot moved to cut out the desired shape. One difficulty with this approach is that small registration errors in each step tend to add up. Four alternative methods are: (1) imaging the robot within the field-of-view of the x-ray apparatus; (2) imaging the hole machined by the robot; (3) tactile search for the canal; and (4) surgeon guided designation of landmark features [10].

External fiducials of known geometry visible in all images can also be used to co-register multiple X-ray images by locating the fiducials in the images and using their type and position to compute the camera pose relative to the fixed reference frame [12, 11, 5]. The challenges for this type of registration are the design of a suitable intraoperative fiducial system for RTHR and the development of suitable image processing methods to locate the fiducials to sub-pixel accuracy in the X-ray images with minimal surgeon intervention. Registering X-ray images to CT data is more difficult. External and internal fiducials are impractical. Pinless or anatomy-based methods 2D to 3D registration methods, such as described in [3, 11], rely on good initial camera pose estimations and high quality CT data.

Computer-integrated RTHR: proposed system and protocol

Figures 2 and 3 show the proposed system architecture and protocol for computer-integrated RTHR. In the preoperative phase, the femur with the failing implant is scanned on a CT machine to obtain volumetric data and x-ray scouts. For image and robot registration, we can use implanted markers or design external fiducials that will be imaged with the femur. The CT slices, together with the scout views and their view pose information are then loaded into the preoperative workstation. The images can be registered using either the external fiducials or anatomy-based registration techniques. The system then presents the surgeon with an image spreadsheet containing the X-ray and CT data. The spreadsheet, an extension of ORTHODOC, also serves as an interface to allow the surgeon to select and evaluate implant types, sizes, and positions, and to define cement cut volumes. One or more preoperative plans can be defined and stored. The output of the preoperative step is a set of co-registered preoperative images and one or more preoperative plans consisting of an implant type, size, and position and the shape and position of the cement cut volume.

In the intraoperative phase, manual surgery will proceed normally until the old implant is removed and the cement that can be easily removed manually from the proximal femur is out. To remove the remaining cement, the surgeon will first place the femur in a specially designed radiolucent fixation device rigidly attached to the robot. Intraoperative X-rays will be obtained and registered to the fixation device, to each other, and to the preoperative plan while the robot locates the fixator, thus establishing a common intraoperative coordinate system. To allow the validation of the preoperative plan, the system will display the outline of the volume to be cut superimposed on the intraoperative X-rays. If necessary, the surgeon may adjust the surgical plan, either by repositioning the cut volume or by modifying its shape (see above). This process must take less than 10 minutes. Once the surgeon has verified the plan, the designated volume will be cut out using the same material removal strategy as that employed by ROBODOC for PTHR. If necessary, additional images will be acquired to define additional cement cut volumes.

The robot will then cut out a conservative initial volume corresponding to the material that the surgeon definitely wants to remove. Additional images will be taken, registered, and compared to the planned cut volume. These images will be used to assess what material still must be removed and to update the registration of the robot to the patient, permitting more accurate positioning of subsequent cuts. The surgeon will then instruct the robot to remove additional cement volumes, take additional X-ray images, and select a final implant model and position using the most

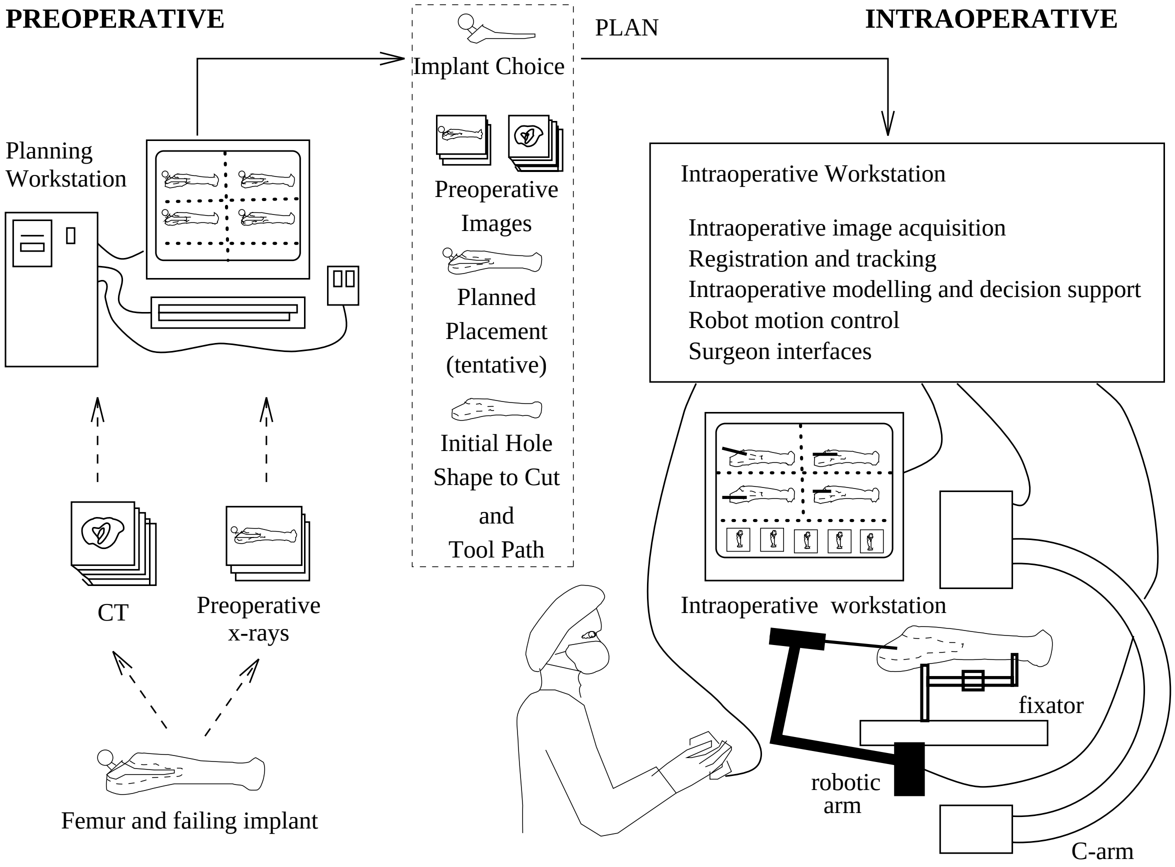

Figure 2: System for Revision Total Hip Replacement Surgery.

recent images. The robot will then cut it the final shape. Once the femoral cavity for the new implant is prepared, the robot will be removed from the surgical field and manual surgery will proceed.

We plan to incrementally modify the PTHR ROBODOC system to allow us to collect data, get early feedback from the surgeon, and assess the importance and degree of sophistication of the missing components. Concurrently, we will develop other capabilities, such as CT image processing and registration methods, which will be integrated to the system later.

Preliminary results

CT artifact removal

As discussed earlier, the best approach for reducing metal-induced CT artifacts is to correct the raw projection (sinogram) data before image reconstruction. Since access to these projection data is generally problematic, we have chosen as a practical alternative the simulated projection approach. Projection data are simulated by forward projecting the corrupted CT images. These simulated projections are then modified to correct for the data missing in the original (true) projections because of the x-ray opacity of metal. Finally, new CT images are reconstructed from the modified projections.

A variation of this method, which to our knowledge has not been considered before, relies on the use of scout images to improve the modification of the simulated projections. Scout images are projection data and have a standard, well-documented, and easily accessible format. We are pursuing the idea of capturing on the order of 20-40 scout images, instead of just a couple as in the current practice. By including in the M simulated projections $N < M$ projections with the same scanning parameters as the N scouts, we can base the modification of the simulated projections on true projection data. Scout images have also the potential to be useful on their own to reconstruct either 2D or 3D images [2, 9, 21]. Further, methods developed for image reconstruction from limited views have application in both surgical planning based on 2D X-rays instead of CT images, and in 2D/3D image registration.

X-ray equipment calibration

The extraction of accurate geometric information from X-ray images is central to our strategy. We are de-

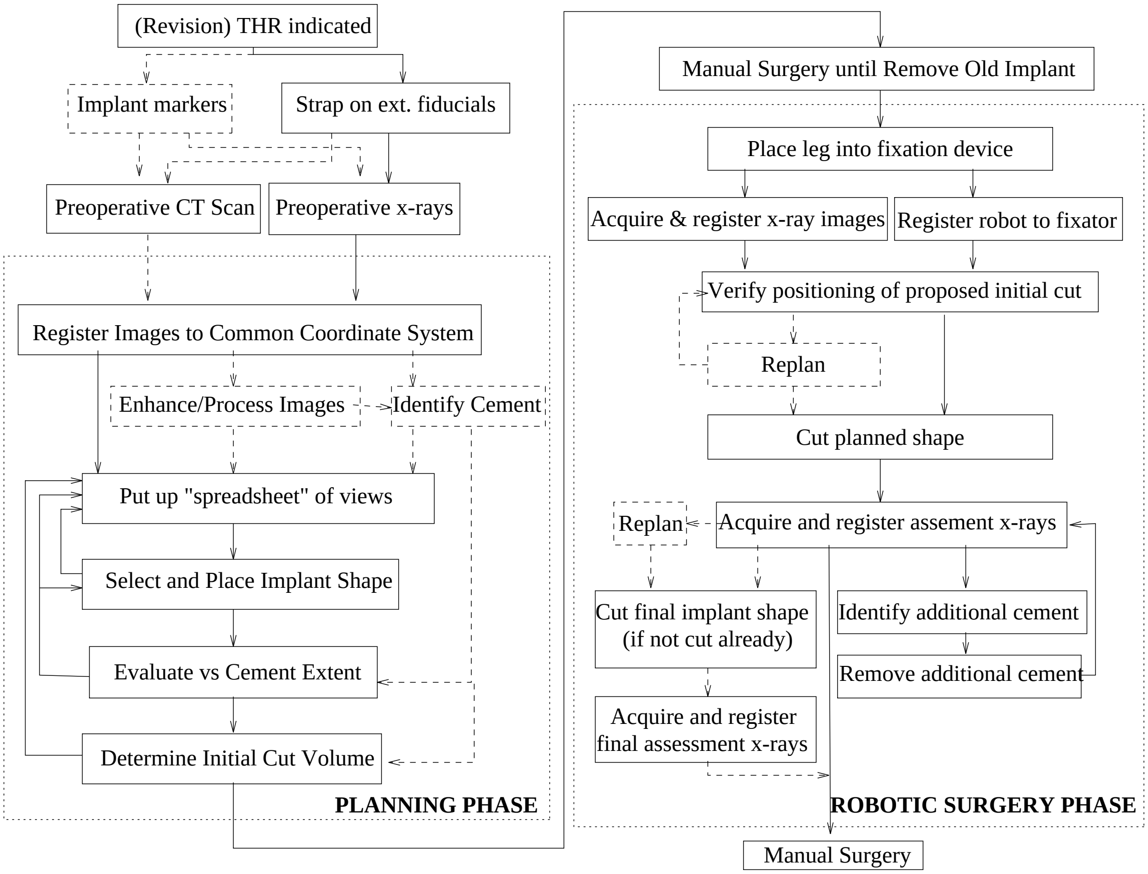

Figure 3: Procedural flow for Revision Total Hip Replacement Surgery. Dotted boxes and lines indicate optional steps and/or possible extensions.

veloping methods both for intrinsic calibration (i.e., for relating points on X-ray images to lines in space relative to the equipment for a single view) and for extrinsic calibration (i.e., for determining the relative imaging geometry between multiple X-ray views). Our approach for internal calibration relies on imaging calibration objects of known geometry placed between the X-ray source and image plane. For external calibration, we rely on identifying homologous features (points and lines) within multiple X-ray images to compute the appropriate camera transformations.

Anatomy-based matching of a CT scan with X-ray views

We model X-ray views with a perspective transformation, whose parameters are determined by calibration, and use image-based techniques to determine the relative imaging geometries for multiple views. Given one or more X-ray images, our problem is to find the best coordinate transform (rotation and translation) between the coordinate systems associated with the CT scan and the X-rays, such that the X-rays best represent the projection of the anatomical structures present in the patient's CT scan. The main characteristic of our approach is to model the anatomy using a set of surfaces extracted from the CT-scan [7, 14] and to superimpose precomputed silhouettes of the surfaces with contours extracted from the X-rays.

We propose a two-stage method. The first stage consists in a crude positioning of the X-rays with respect to the CT scan. We are currently studying several choices: positioning by an operator (manual), automatic matching to the best candidate among a library of precomputed views, or positioning using projective invariants. The second stage consists in refining the pose. To refine the pose, we hypothesize matches between points on the X-rays and points on the projected surface silhouettes. Using the matches, we compute a rotation and translation that minimizes the sum of distances in 3D between the 3D silhouette points and the 3D lines between each point on the X-rays and the center of perspective.

Image spreadsheet

We are developing an image spreadsheet for selectively viewing X-ray images, CT cross-sections, and 3D vol-

Figure 4: Image spreadsheet showing four windows and a thumbnail.

umetric reconstructions (Figure 4). The spreadsheet maintains the images co-registered and allows manipulating overlays on them. It includes standard image-processing tools, such as histogramming, intensity adjustments, and zooming and panning. It allows the user to specify the number of windows desired (4 in the figure) and maintains a scrollable window (bottom window) containing "thumbnail" views of the case images, which can be displayed by dragging and dropping them in any window. New images can be generated, saved, and added as thumbnail images to the bottom window. Volume data, such as 3D CAD implant models and cut volumes can be overlayed on bitmap images. The user can manipulate and position the volumes with the mouse. The system computes the projection and maintains them co-registered. We plan to implement and test the usefulness of semi-automatic positioning using surgeon-defined correspondences.

Interactive cut volume definition

We have augmented ORTHODOC with an interactive cut volume definition module. The surgeon first segments out the bone cement by creating a contour that defines the bone cement to be removed in several CT slices. The contour data is feed into a cut path generator algorithm which outputs a contour identifying the computed robot cut path. The cut path is created by examining all the contours that the user has generated and constructing a cut path that takes into account the cutter radius and allows for straight insertion along the vertical axis (Figure 5).

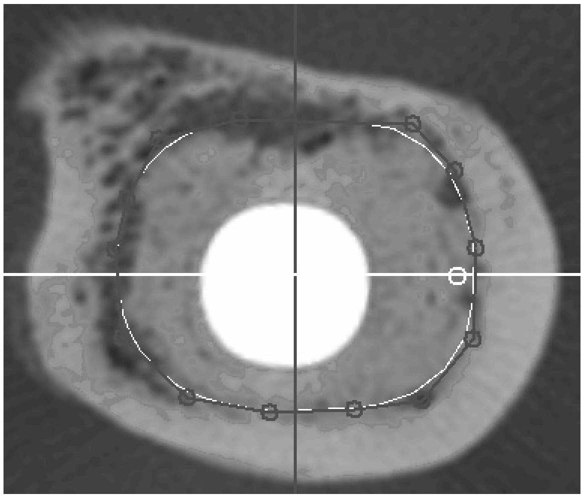

Figure 5: CT cross showing the desired (outer boundary) and system-generated (inner boundary) cut volume contour.

Cement machining

We have designed and conducted experiments to simulate as closely as possible cement removal. In one experiment, we tested whether the cutters currently used in ROBODOC PTHR are adequate to cut bone cement by cutting circular shapes in a hard plastic material with density similar to bone cement. To determine accuracy, the diameter of the cavities was measured and compared to the planned diameter, obtaining satisfactory results for shape and position accuracy. In another experiment, we tested how deep we can cut in bone cement and still achieve the accuracy we need. With the current instrumentation, the ROBODOC system can cut an implant cavity about 200 mm deep along the axis of the bone. We are in the process of determining at which point tool tip deflection becomes significant.

Conclusion

Our goal is to develop and clinically demonstrate a computer-integrated system to assist surgeons in revision total hip replacement surgery. We believe that in building this system, we will develop innovative responses to some crucial technical challenges that will gate the application of similar systems to many orthopaedic and other surgical problems.

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