# X-Ray Image Based Navigation for Hip Osteotomy

Project Proposal

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## Summary

Periacetabular osteotomy (PAO) is a joint reconstruction surgery for increasing femoral head coverage and improving stability in patients with developmental dysplasia of the hip (DDH). Our research mentors have previously developed a software package for geometrical and biomechanical planning of PAO called the Biomechanical Guidance System (BGS). One of its key features is intraoperative fragment tracking using a Polaris optical system. However, because of the wider availability of C-arm imagers in hospitals and surgeon familiarity with fluoroscopy, an implementation of BGS utilizing x-ray navigation is desired.

The first aim of this project is to develop a protocol and software pipeline for an X-ray image guided navigation system for performing PAO. The second objective is to compare the proposed pipeline with the current procedure, which utilizes optical tracker navigation. The proposed procedure involves placing several metallic radiopaque BBs on (1) the uncut pelvis to provide a virtual reference frame, and (2) the bone fragment undergoing realignment. Prior to surgery, two C-arm images will be acquired at different poses, de-warped, and registered to a preoperative CT model. A small (3x3x5 cm) fluoroscopic tracker (FTRAC) will be attached to the pelvis to recover image pose. Following fragment realignment, two more C-arm images will be acquired and registered to the CT model. The BGS software will display biomechanical and radiographic data to help the surgeon evaluate whether the realignment has met the preoperative plan.

## Background and Significance

DDH is characterized by a malformed acetabulum, or hip socket, exhibiting insufficient coverage of the femoral head and high joint contact pressure. Such elevated pressure can lead to complications such as degenerative osteoarthritis and fracture of the acetabular labrum [Millis 1995]. DDH is most prevalent in young women, often under the age of 30. Hip arthroplasty is not recommended in patients who are young and active or have unilateral dysplasia. These patients are likely to outlive mechanical joint replacements and require revision surgery, and there are concerns regarding prosthetic surface durability and preservation of bone stock. For these individuals, reconstructive surgeries are preferable to prosthetics.

One effective joint reconstruction surgery is periacetabular osteotomy (PAO), which reorients the acetabulum to increase femoral head coverage and lower joint contact pressure. In particular, the Ganz osteotomy [Ganz 1988] utilizes a single incision and four osteotomies, and it preserves the patient's posterior column and vascular supply.

Our research mentors have previously developed a software package for computer-assisted PAO named the Biomechanical Guidance System (BGS) which features both preoperative planning and intraoperative fragment tracking [Murphy 2010]. The BGS procedure begins with acquisition of a full pelvic CT scan and manual segmentation of the femur and pelvis. The Lunate-Trace algorithm is used to segment and generate a surface mesh model of the acetabulum, and radiographic angles are measured from the CT image. During the planning stage, the software computes contact pressures via Discrete Element Analysis, and it suggests a reorientation of the acetabulum that minimizes simultaneous peak contact pressure in sitting, standing, and walking positions [Murphy 2010].

The current BGS system is capable of intraoperative fragment tracking using a Polaris 3D position sensor. After performing a pivot calibration, a dynamic rigid body (DRB) is attached to the pelvis to serve as a fixed reference frame. A gross model-to-patient registration is performed by touching a surgical tool tip (also equipped with a DRB) to four known anatomical locations on the pelvis, and an iterative closest point algorithm performs fine surface registration. The surgeon drills four confidence points on the ilium to serve as a fixed reference frame. After the osteotomy, the surgeon updates the model-to-patient registration by touching the four confidence points on the ilium and the four landmark points on the realigned fragment. BGS displays radiographic angles and biomechanical data indicating how the fragment moved during surgery. If necessary, the surgeon can reorient the fragment and update the registration until the desired outcome is achieved.

As mentioned in the Summary, an X-ray based navigation system for the BGS-assisted PAO would likely appeal to surgeons by relying on the imaging modality with which they are accustomed to working. Moreover, the availability of optical trackers in a typical OR is not likely to be as widespread as the availability of a C-arm imager.

## Technical Approach

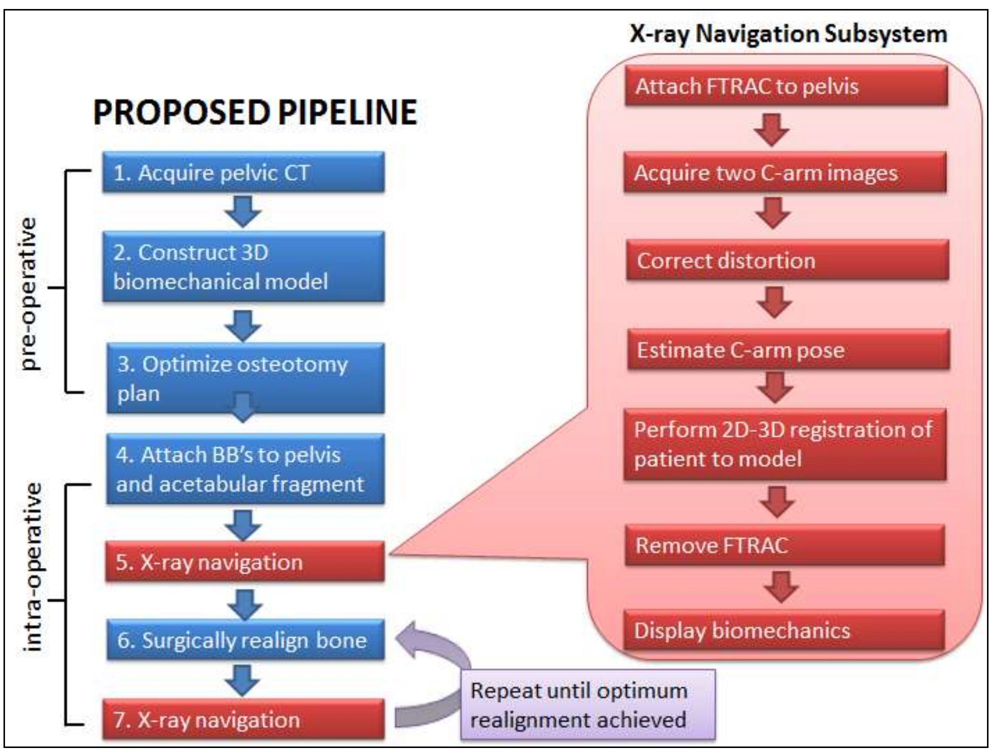



**Figure 1.** Proposed pipeline for x-ray image based navigation for hip osteotomy.

## Procedure Outline

We propose a novel protocol and software pipeline for an x-ray guided navigation system for performing PAO (Figure 1). First the surgeon acquires a preoperative CT scan of the patient's hip region. Next BGS constructs a 3D biomechanical model of the hip and femur and assists in planning the osteotomy. Intraoperative fragment tracking will be achieved using metallic, radiopaque BBs (Figure 2). It should be noted that this is similar to an FDA approved practice for radiostereometry analysis, in which tantalum beads are injected onto bone for tracking in certain orthopedic applications [RSA Biomedical 2009]. In our procedure, four to five BBs are placed (1) on the operative side of the pelvis to serve as a fixed reference frame and (2) on the acetabular fragment. The BBs should be placed 3 to 4 centimeters apart and not be coplanar.

The surgeon also attaches a fluoroscopic tracker (FTRAC) [Jain 2005] to the pelvis for estimating the image pose. The FTRAC is a fiducial containing points, lines, and ellipses in a configuration that allows the 6DOF C-arm pose to be uniquely calculated from any view. During initial testing, we will rigidly attach the FTRAC to the pelvis using a bone screw during image acquisition, and then remove the FTRAC before reorienting the acetabulum. Later we will investigate methods for non-rigid attachment. As long as the FTRAC remains stationary with respect to the patient while acquiring the two C-arm images, it may still be possible to recover image pose.

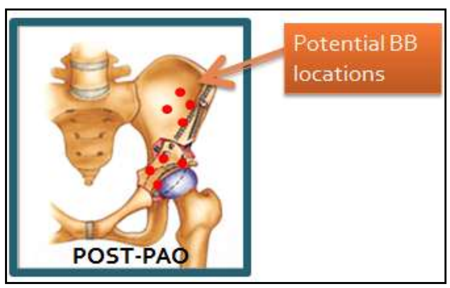



**Figure 2**. Possible placement of BBs on ilium and acetabular fragment.

The raw fluoroscopic images are warped due to the curved shape of the detector and interference from the Earth's magnetic field. In addition, this distortion varies with C-arm position. We will utilize existing software to correct this distortion. A metallic grid phantom is placed on the detector and a single image is acquired preoperatively. A distortion map is created by fitting a fifth degree Bernstein polynomial to the data and interpolating over all pixels in the image. If time permits, we may begin investigating principal component analysis (PCA) based correction, which has the added advantage of yielding pose-dependent distortion maps [Chintalapani 2007].

After rigid fixation of the BBs, non-rigid attachment of the FTRAC, and creation of the distortion maps, two C-arm fluoroscopy images will be acquired at roughly 30° separation. Existing BGS software will segment the BBs and perform 2D/3D registration to determine the preoperative location of the pelvis and fragment. The first step in 2D/3D registration is using the FTRAC to estimate C-arm pose. For this step we plan to utilize an existing implementation of expectation conditional maximization (ECM) [Kang 2011]. Although this algorithm is correspondenceless, its performance is sensitive to the estimated pose used for initialization. We plan to research and implement a method for automatically initializing the ECM algorithm. Existing BGS software generates a digitally reconstructed radiograph (DRR) from the CT model using tri-linear interpolation and Siddon's ray tracing method with GPU acceleration [Otake 2011]. The estimated pose is repeatedly updated until an objective function based on mutual information is optimized.

Before cutting the fragment, the surgeon will remove the FTRAC. Once the fragment has been realigned, the surgeon will confirm that the new configuration matches the biomechanical plan. This is done by repeating the x-ray navigation procedure described above. First the FTRAC is attached to the pelvis – not necessarily in the same location as before –and two C-arm fluoroscopy images are acquired at 30° separation. Image pose will be estimated by the ECM algorithm and 2D/3D registration will be performed. BGS will display geometrical and biomechanical data to help the surgeon assess how the fragment moved during surgery. Fragment position and orientation will be shown in the Bergman frame, which is a standard coordinate system for hip biomechanics. If the surgeon decides that the acetabular cup and femoral head are still inadequately positioned, realignment and imaging may be repeated until the desired outcome is achieved.

### Procedure Evaluation (What if we just integrated this with the deliverables?)

The proposed pipeline will be compared with the previously developed method for PAO, which uses intraoperative optical fragment tracking. Experimental results will be obtained by mock surgeries on a pelvic phantom and cadavers. Several criteria will be assessed using the optical tracker results as the ground truth, including

1. Accuracy in registration and fragment tracking
2. Extra time added to the surgery

## Deliverables

### Minimum

1. *Development of a surgical pipeline/protocol from acquiring pre-op CT to displaying post-op biomechanics.*

    The term "protocol" refers to a specific, repeatable workflow consisting of every sequential step in the proposed method. The term "pipeline" refers to a block diagram representing this protocol. This deliverable will be complete when the proposed method can be successfully carried out by following the same set of steps in the same order.

2. *Optimization of BB placement and development of a method for firmly attaching BBs to bone.*

    Judicious choices of confidence points on both the fixed bone and the fragment are important to the success of the proposed method. For example, BBs placed too close together may reduce the tracking accuracy. This deliverable will be complete when (1) any method of selecting non-coplanar confidence points has been proven to be consistently effective and (2) when BBs can be securely attached and detached from bone with no harm to the patient.

3. *Comparison of experimental results obtained from mock surgery using (i) proposed method (x-ray navigation) and (ii) current BGS method (optical tracker navigation).*

Both methods will be employed in a mock surgery on a pelvic phantom as many times as necessary to achieve consistent biomechanical and radiographic data and procedure times. Data from the proposed method will be compared using the optical tracker results as ground truth. Evaluation criteria may include registration accuracy (such as mean target error) and computation or procedure times. This deliverable will be complete when the shortcomings and advantages of each method have been summarized in a report.

## Expected

1. *Integration of x-ray navigation procedure with existing BGS software.*

The user will have the option of selecting "X-Ray Navigation" or "Optical Navigation" from within a single interface, eliminating the need for two distinct software suites. This deliverable will be complete when the proposed method has been fully integrated into the conventional method's existing interface.

2. *Comparison of experimental results obtained from cadaveric surgery using (i) the proposed method (x-ray navigation) and (ii) the current BGS method (optical tracker navigation).*

This deliverable will be similar to Minimum Deliverable No. 3, but the phantom study will be replaced by a cadaveric study. This deliverable will be complete when the particular shortcomings and advantages of each method have been assessed on a cadaver and summarized in a report.

3. *Investigation of non-rigid attachment of FTRAC*

One disadvantage of the current BGS method is the need for attaching a dynamic rigid body directly to the hip bone. In contrast, the FTRAC does not necessarily need to be attached to the bone, so long as it remains stationary while acquiring the two fluoroscopy images. This deliverable will be complete when pose estimation is successfully performed with a loosely attached FTRAC in a minimally invasive manner, and the registration accuracy has been compared to that achieved with a rigidly attached FTRAC.

## Maximum

1. *Development of a technique for automatically initializing the ECM pose estimation algorithm.*

Currently, BGS initializes the EM algorithm by running one iteration of Pose from Orthography and Scaling with Iterations (POSIT) [Dementhon 1995]. This solution is not ideal because POSIT requires knowledge of matching feature points between the image and object. This deliverable will be complete when an automatic approach for initializing the ECM algorithm is developed that achieves comparable or improved estimation of image pose.

2. *Investigation of alternatives to FTRAC.*

It is possible that pose estimation accuracy may decrease when the FTRAC is non-rigidly attached to the pelvis compared to rigid attachment. In addition, the existing pose estimation software only utilizes the point fiducials in FTRAC, rendering the linear and elliptical fiducials superfluous. Therefore, we will investigate alternative hardware that could replace FTRAC. This deliverable will be complete when at least one such method has been tested in the pipeline and its results compared to those of FTRAC.

# Management Plan

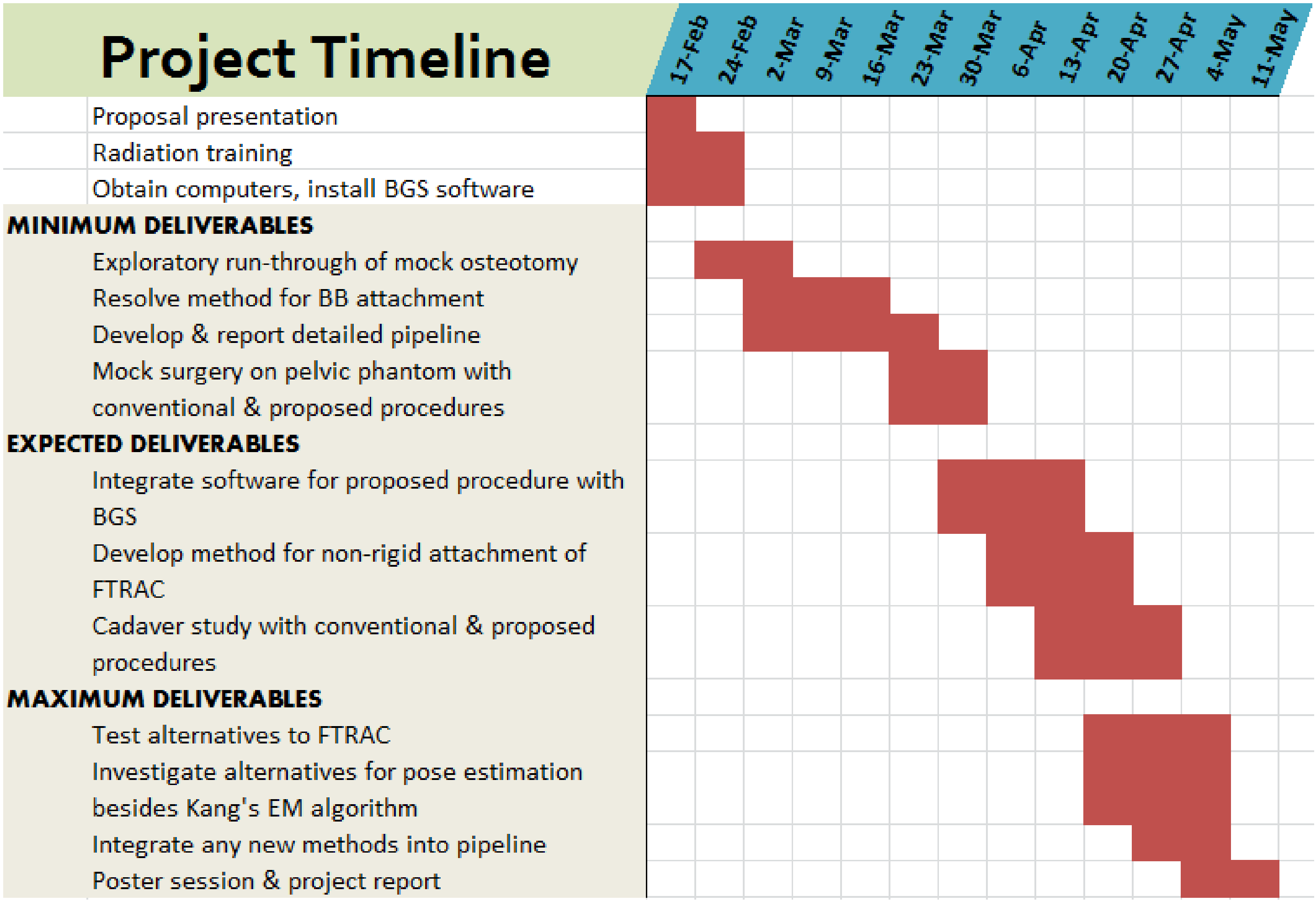
## Dependencies

| Status | Description |
|---|---|
| **Completed** | Obtain access to mock OR. |
| **Completed** | Agree on regular meeting times with mentors. |
| **In progress** | Obtain radiation training from Dr. Granlund in order to operate the C-arm. |
| **In progress** | Obtain computers capable of running the BGS software for pose estimation and 2D/3D registration. Although not necessary, portable computers that could be brought into the mock OR are desired. |
| **In progress** | BGS software and sample data sets must be installed on the machines we use. |

## Milestones

| Target Date | Milestone Description |
|---|---|
| FEB 21 | Present project proposal to class. |
| FEB 23 | Obtain radiation training to operate C-arm in mock OR. Work with mentors to get computers capable of running BGS software (portable laptops that could be brought into the mock OR are desirable). |
| MAR 2 | Gain familiarity with existing BGS software by performing an initial run-through of a mock osteotomy. |
| MAR 16 | Resolve a method to firmly attach metallic BBs to pelvis. |
| MAR 23 | Finish report detailing the proposed pipeline. |
| MAR 30 | Demonstrate mock surgery on pelvic phantom using both the conventional and proposed procedures. Compare experimental results from both methods. |
| ***Minimum Deliverables Have Been Achieved*** | |
| APR 13 | Integrate software for the proposed procedure with BGS. |
| APR 20 | Develop method for non-rigid attachment of FTRAC and integrate into pipeline. |
| APR 27 | Conduct cadaver study using both the conventional and proposed procedures. Compare experimental results from both methods. |
| ***Expected Deliverables Have Been Achieved*** | |
| MAY 4 | Tested alternatives to FTRAC and investigated other approaches for pose estimation besides Kang's EM algorithm. Integrate any new methods into the pipeline. |
| ***Maximum Deliverables Have Been Achieved*** | |
| MAY 10 | Poster session and project report due |

## Timeline


Project Timeline
17-Feb
24-Feb
2-Mar
9-Mar
16-Mar
23-Mar
30-Mar
6-Apr
13-Apr
20-Apr
27-Apr
4-May
11-May
Proposal presentation
Radiation training
Obtain computers, install BGS software
MINIMUM DELIVERABLES
Exploratory run-through of mock osteotomy
Resolve method for BB attachment
Develop & report detailed pipeline
Mock surgery on pelvic phantom with conventional & proposed procedures
EXPECTED DELIVERABLES
Integrate software for proposed procedure with BGS
Develop method for non-rigid attachment of FTRAC
Cadaver study with conventional & proposed procedures
MAXIMUM DELIVERABLES
Test alternatives to FTRAC
Investigate alternatives for pose estimation besides Kang's EM algorithm
Integrate any new methods into pipeline
Poster session & project report

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