X-Ray Image Based Navigation for Hip Osteotomy

Project Proposal Presentation

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Course:	Computer Integrated Surgery II (EN.600.646)

Project Aims

We would like to

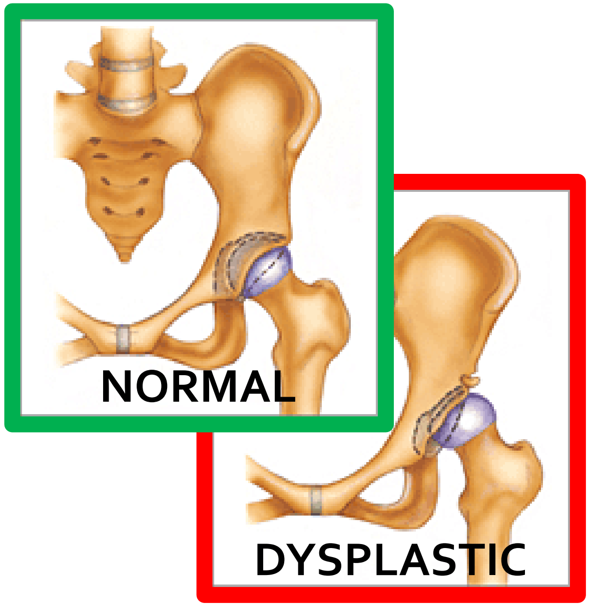
1. design and implement a **surgical pipeline** for X-ray image-based navigation applicable to hip osteotomy, and

1. **experimentally compare** the proposed method with the current BGS method (optical tracker navigation)

Background

DDH – Developmental Dysplasia of the Hip

- DDH is a congenital dysplasia, mostly affecting women under the age of 30.
- The malformed hip socket (acetabulum) is about 20% smaller than that of a normal hip, leading to
  - poor femoral head coverage,
  - increased contact pressure,
  - and degeneration of cartilage (eventually, arthritis).

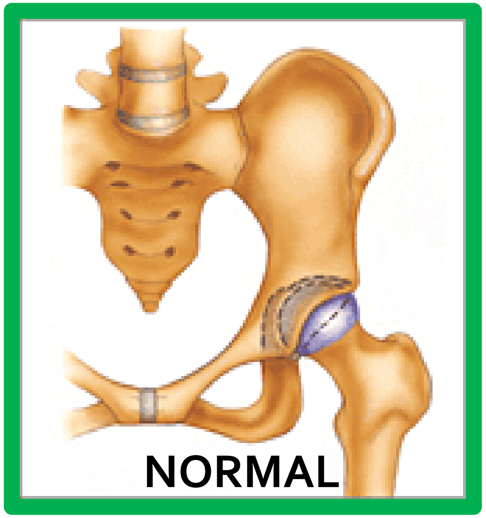


D. R. Cooperman, R. Wallensten, and S. D. Stulberg, "Acetabular dysplasia in the adult." *Clin Orthop Relat Res*, no. 175, pp. 79-85, May 1983.

Background

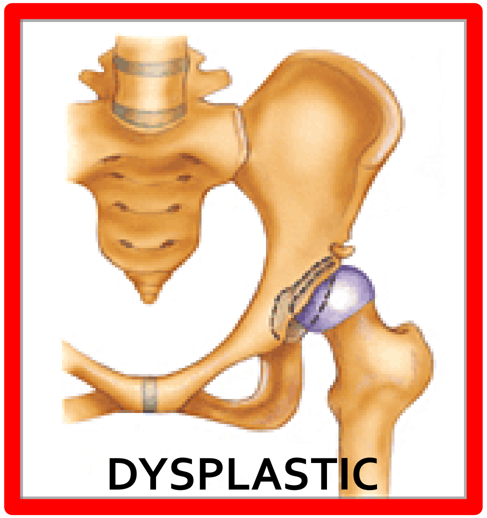
DDH – Developmental Dysplasia of the Hip

Normal Hip vs. Dysplastic (malformed) Hip



“cup”-shaped acetabulum

vs.

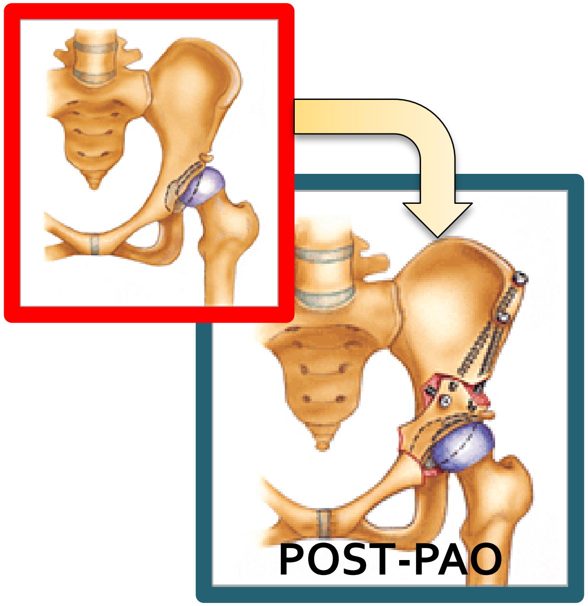


“dish”-shaped acetabulum

Background

PAO – Periacetabular Osteotomy

- PAO is a joint reconstruction surgery shown to correct DDH, alleviating pain and reducing the risk of complications in most patients.
- The procedure realigns the acetabular cup, seeking to
  - increase femoral head coverage,
  - decrease contact pressure, and
  - improve stability.

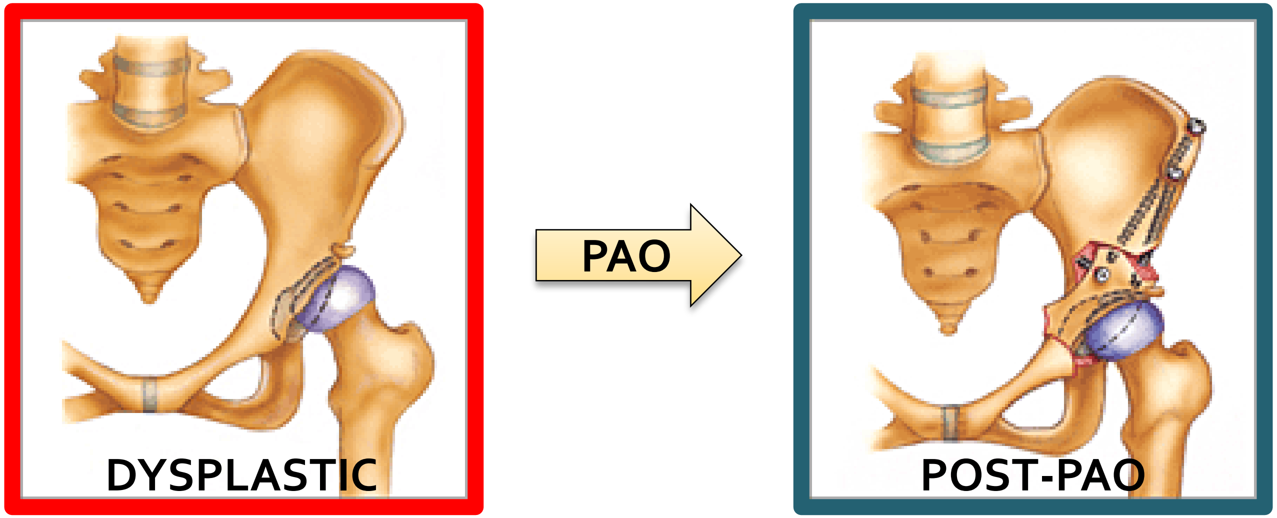


R. Ganz, K. Klaue, T. S. Vinh, and J. W. Mast, "A new periacetabular osteotomy for the treatment of hip dysplasias. Technique and preliminary results." *Clin Orthop Relat Res*, no. 232, pp. 26-36, Jul 1988.

Background

PAO – Periacetabular Osteotomy

Dysplastic (malformed) Hip Pre-PAO vs. Post-PAO



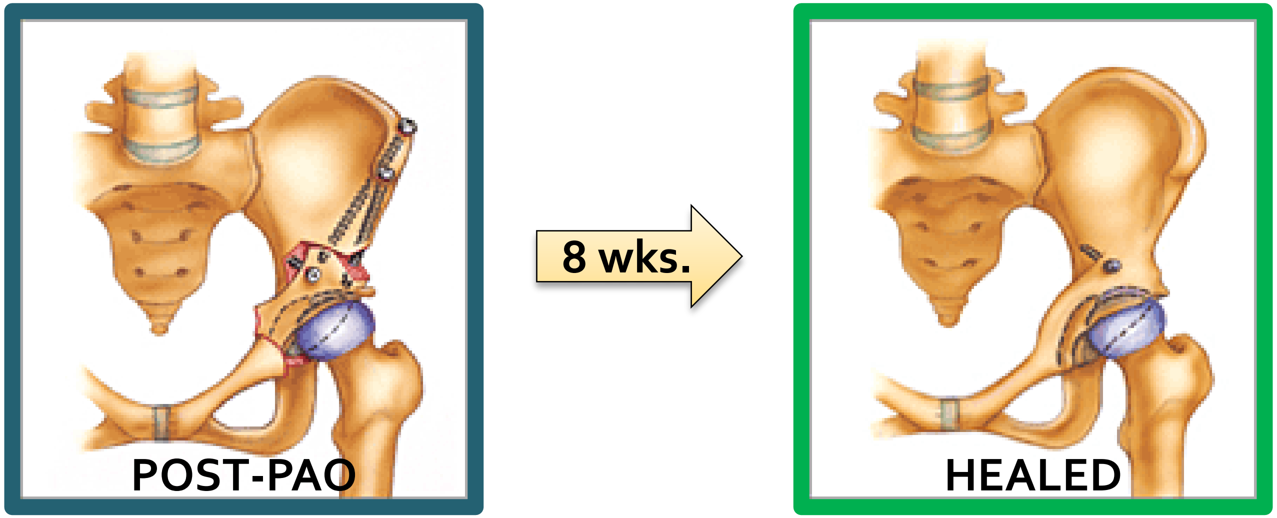
"dish"-shaped acetabulum

"cup"-shaped acetabulum

Background

PAO – Periacetabular Osteotomy

Post-PAO Hip vs. Healed Hip



Background

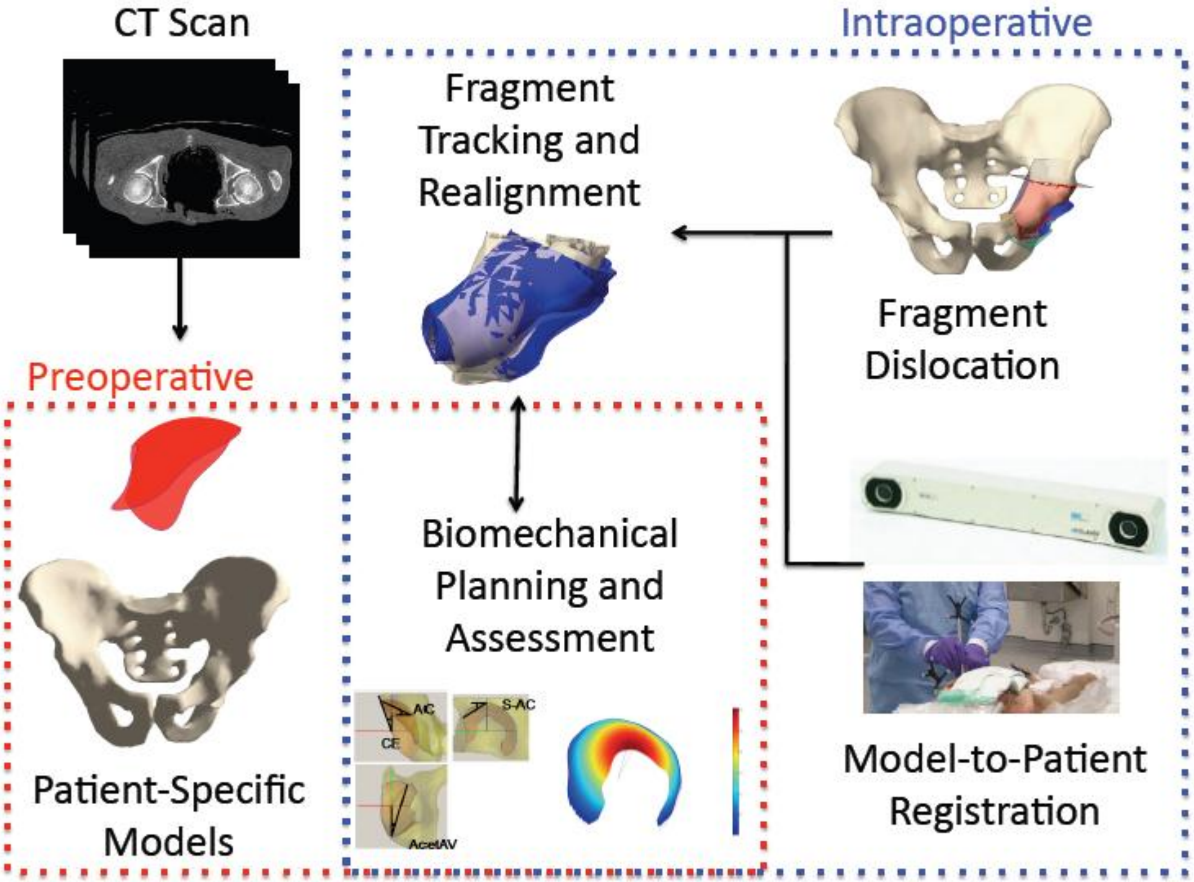
BGS – Biomechanical Guidance System

- The BGS is software used to predict realignment in PAO.
- Using geometrical and biomechanical planning, the software allows the surgeon to
  - develop a preoperative plan for the surgery,
  - update this plan intraoperatively via fragment tracking (currently external), and
  - quantitatively assess fragment realignment during surgery.

J. Lepistö, M. Armand, and R. S. Armiger, "Periacetabular osteotomy in adult hip dysplasia - developing a computer aided real-time biomechanical guiding system (BGS)," Suomen Ortopedia ja Traumatologia, vol. 31, pp. 186-190, Feb 2008.

Background

BGS – Biomechanical Guidance System



CT Scan

Intraoperative

Fragment Tracking and Realignment

Fragment Dislocation

Preoperative

Biomechanical Planning and Assessment

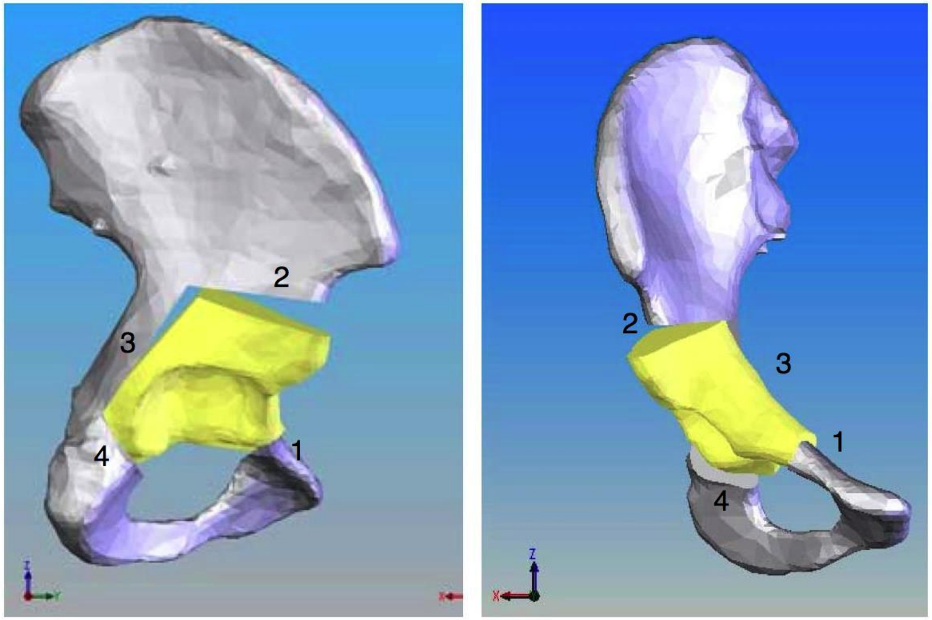
Patient-Specific Models

Model-to-Patient Registration

Background

BGS – Biomechanical Guidance System

- **Ganz Osteotomy**
  - 1 incision
  - 4 osteotomies
  - preserves posterior column and vascular supply (less pain)
- The BGS allows the surgeon to optimally place the fragment (yellow).



The cuts of the osteotomy are numbered according to the order in which they are made.

Current BGS Method

Optical Tracker-Based Navigation

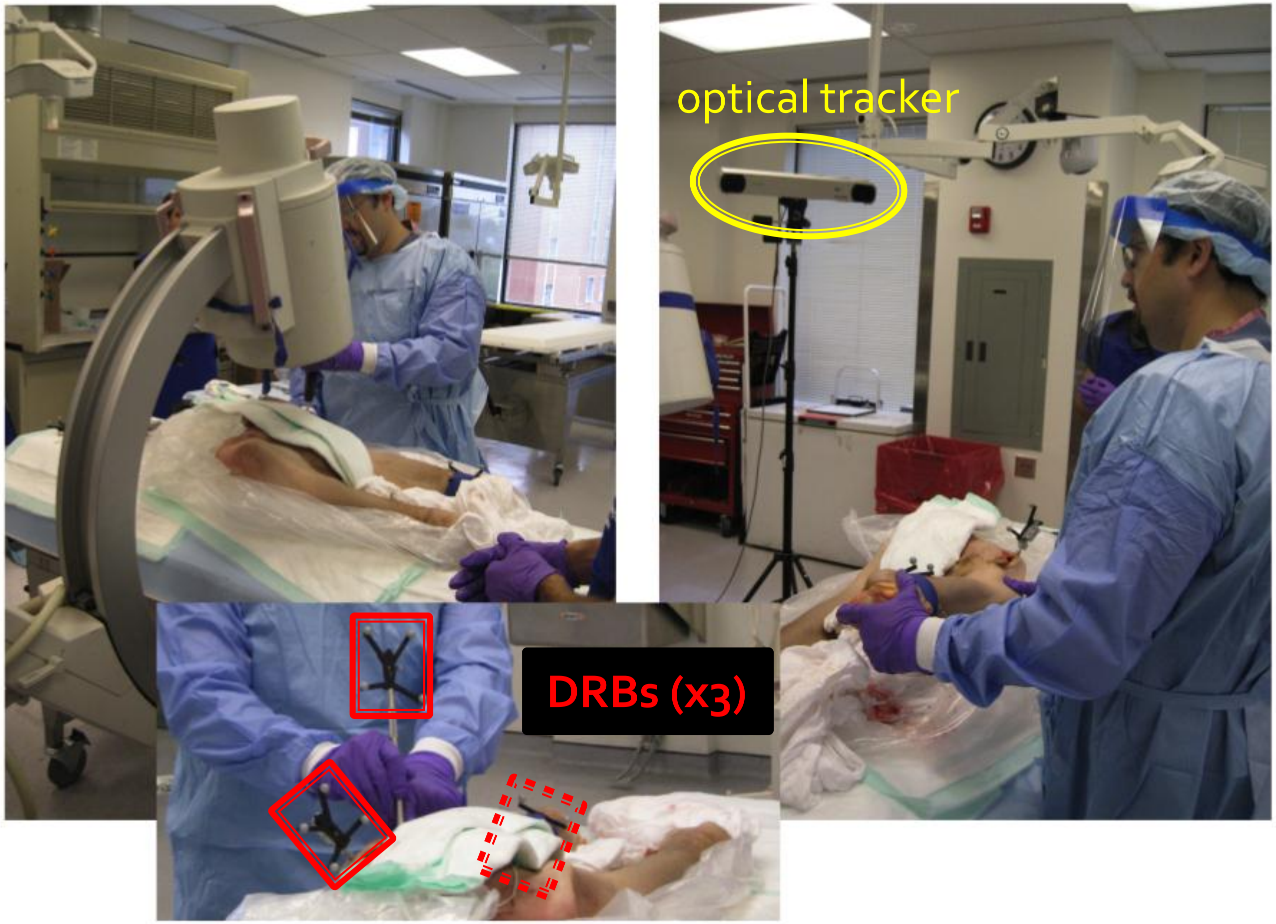
Polaris camera

Required equipment:

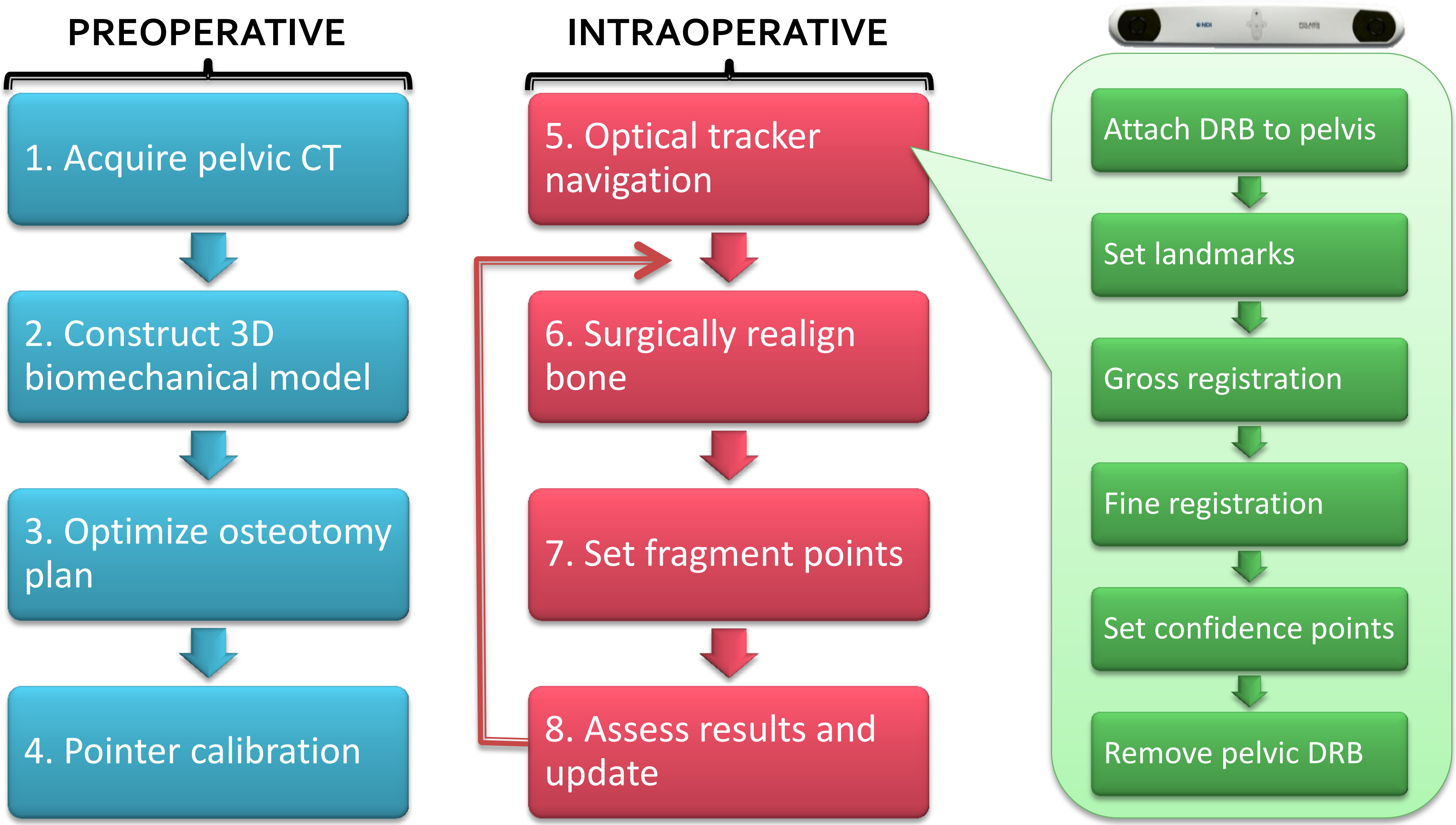
- Polaris camera
- Dynamic Rigid Body (DRB)
  - Pelvis
  - Tool
  - Femur

DRB

Current BGS Method (OR Setup)



Current BGS Method (Workflow)



PREOPERATIVE

1. Acquire pelvic CT
2. Construct 3D biomechanical model
3. Optimize osteotomy plan
4. Pointer calibration

INTRAOPERATIVE

5. Optical tracker navigation
6. Surgically realign bone
7. Set fragment points
8. Assess results and update

- Attach DRB to pelvis
- Set landmarks
- Gross registration
- Fine registration
- Set confidence points
- Remove pelvic DRB

Motivation

Goal:

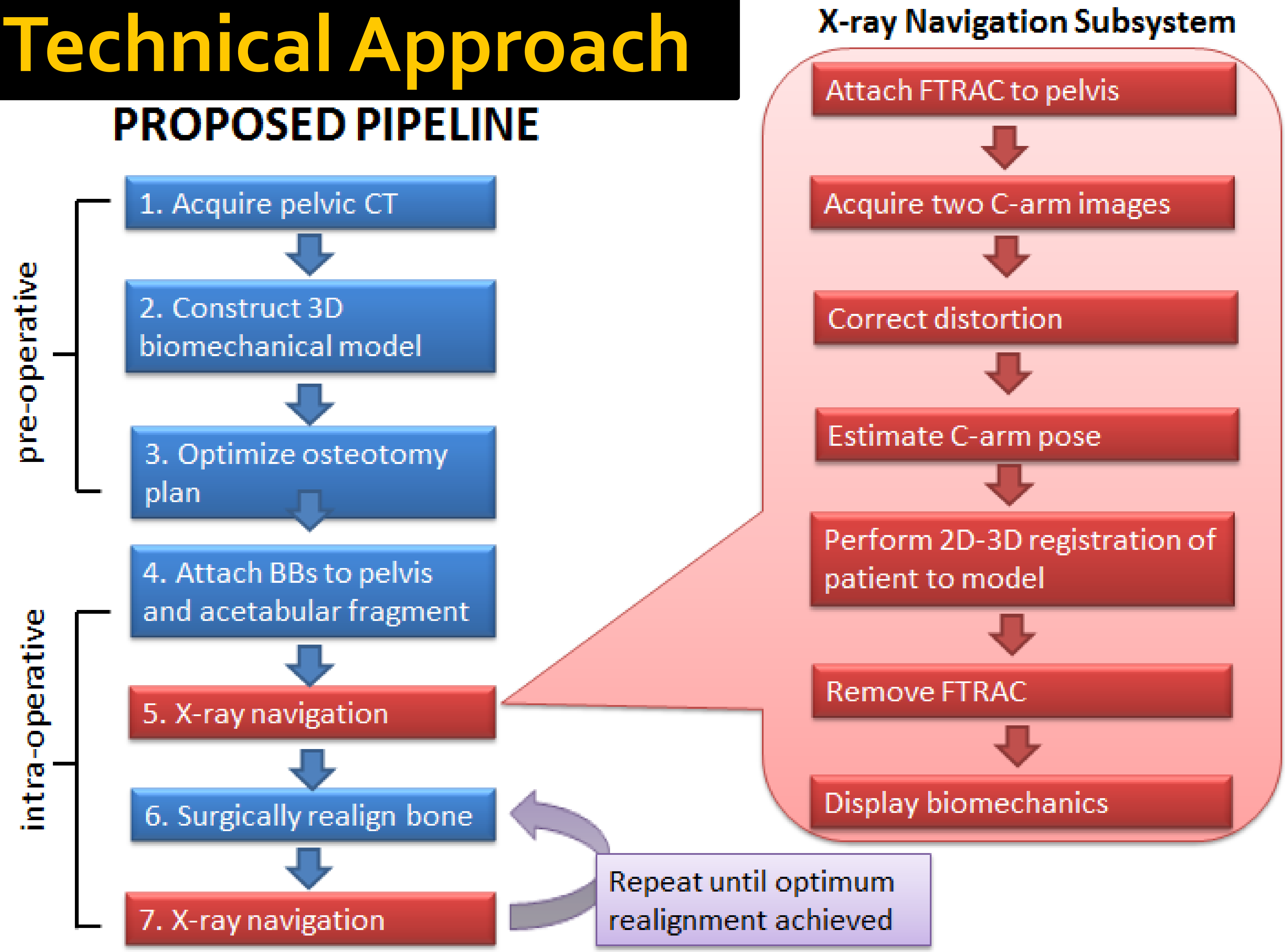
We want to replace optical tracker navigation with X-ray navigation.

Why:

- X-ray navigation more in line with what surgeons are already doing
- Surgeons occasionally have disputed the results of the optical tracker method

Otake Y, Armand M, Armiger R, Kutzer M, Basafa E, Kazanzides P, Taylor R. Intraoperative image based multi-view 2D/3D registration for image-guided orthopaedic surgery: Incorporation of fiducial-based C-arm tracking and GPU-acceleration. Medical Imaging, IEEE Transactions on 2011.

Technical Approach



PROPOSED PIPELINE

pre-operative

1. Acquire pelvic CT
2. Construct 3D biomechanical model
3. Optimize osteotomy plan

intra-operative

4. Attach BBs to pelvis and acetabular fragment
5. X-ray navigation
6. Surgically realign bone
7. X-ray navigation

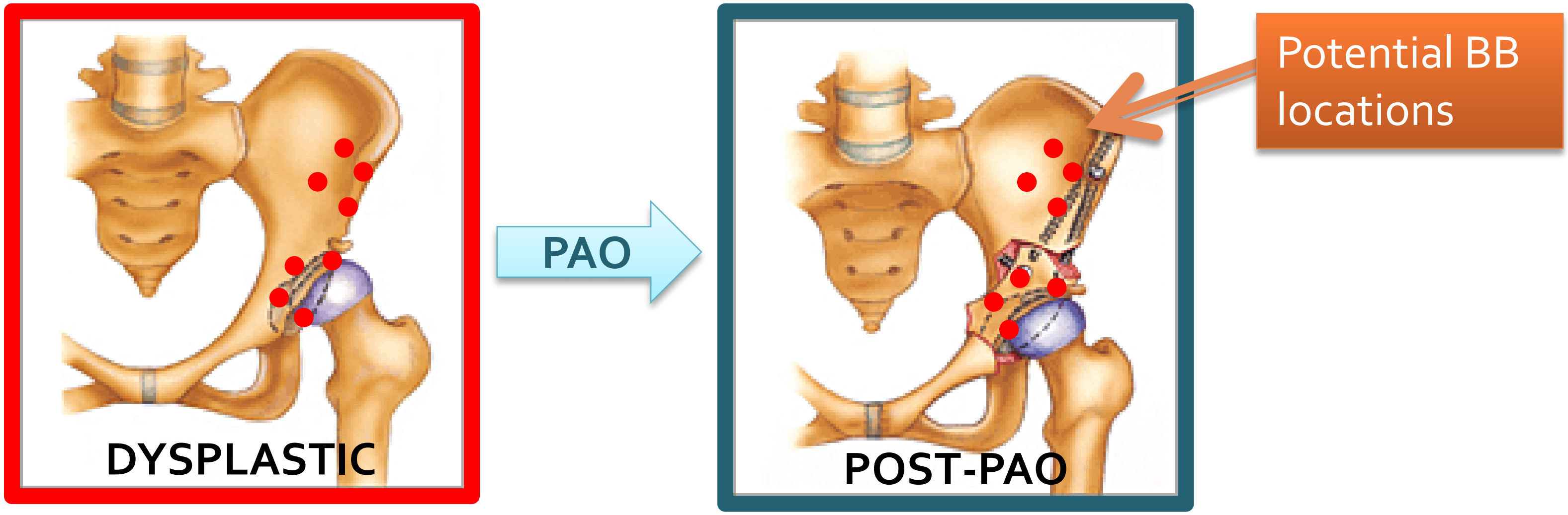
Repeat until optimum realignment achieved

X-ray Navigation Subsystem

- Attach FTRAC to pelvis
- Acquire two C-arm images
- Correct distortion
- Estimate C-arm pose
- Perform 2D-3D registration of patient to model
- Remove FTRAC
- Display biomechanics

Technical Approach

- Metallic radio-opaque BBs attached to
    1. ilium (fixed virtual reference frame)
    2. acetabular fragment
- Tracking BB movement will indicate how bone fragment moved during realignment



Potential BB locations

Distortion Correction

- C-arm image distortion caused by
  - curved detector
  - earth's magnetic field
- Solution: **one-time pose calibration**

Acquire fluoroscopy image at one pose

Fit 5th order Bernstein polynomial

Interpolate over all image pixels

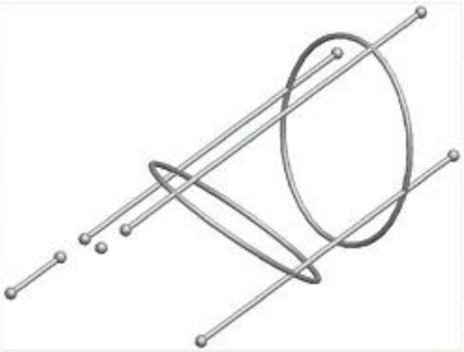
Drawbacks:

- limited accuracy
- ignores pose dependence

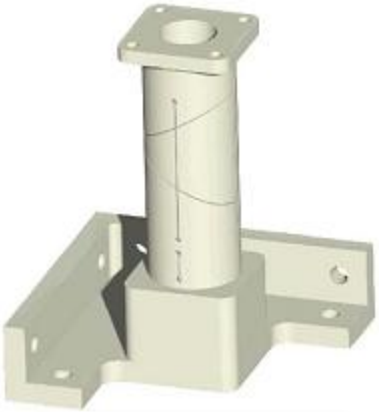
FTRAC for Pose Estimation

FTRAC = fluoroscopy tracking

- Stainless steel fiducials encased in radiolucent housing
- Encodes 6DOF from single image by creating unique view from any angle
- Features: 9 points, 3 lines, 2 ellipses



wire model

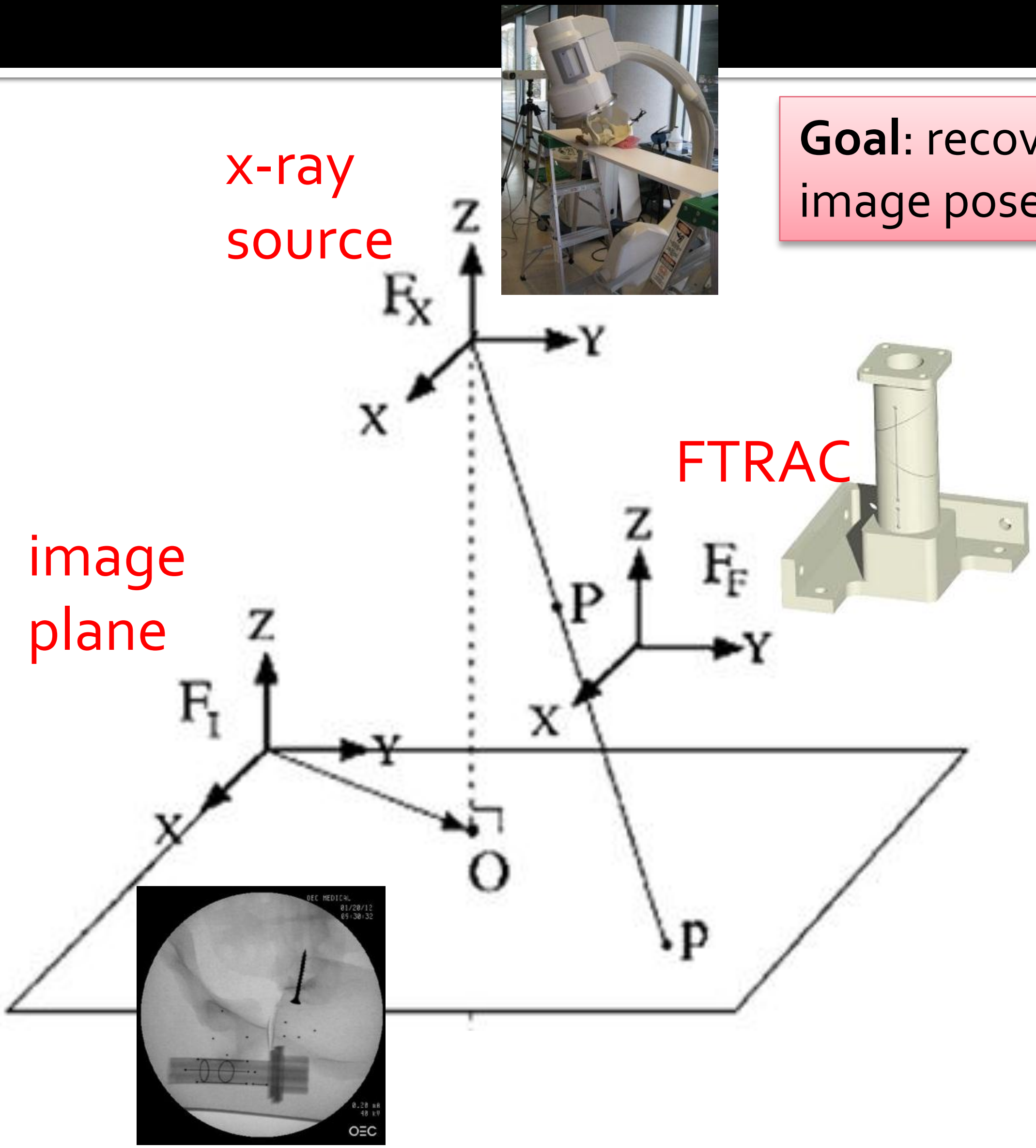


CAD model

x-ray image

. Jain AK, Mustafa T, Zhou Y, Burdette C, Chirikjian GS, Fichtinger G. FTRAC - A robust fluoroscope tracking fiducial. Med Phys 2005 October 2005;32(10):3185-98.

FTRAC for Pose Estimation



Goal: recover the image pose ${}^X F_F$

Imaging Equation

$$p_I = {}^I F_X \, {}^X F_F \, P_F$$

Intrinsic Parameters of C-arm

$${}^I F_X = \begin{bmatrix} -f/s_x & 0 & o_x & 0 \\ 0 & -f/s_y & o_y & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

FTRAC Pose

$${}^X F_F = \begin{bmatrix} r_{11} & r_{12} & r_{13} & T_1 \\ r_{21} & r_{22} & r_{23} & T_2 \\ r_{31} & r_{32} & r_{33} & T_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

FTRAC for Pose Estimation

- Estimate image pose ${}^{X}F_{F}$ using Kang's **expectation-conditional maximization** algorithm
  - Every 3D point assigned a Gaussian **correspondence probability** with each 2D point
  - Advantage: correspondenceless (don't need to match feature points beforehand)
  - Disadvantage: requires initial guess for pose

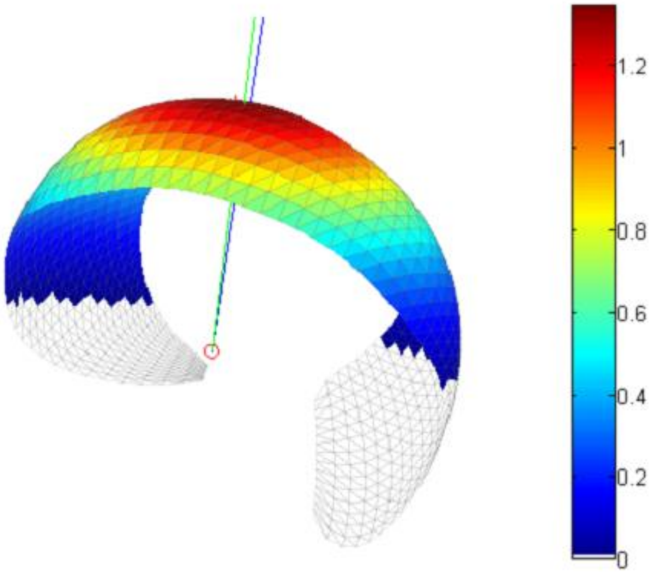
Kang X, Taylor RH, Armand M, Otake Y, Yau WP, Cheung PYS, Hu Y. Correspondenceless 3D-2D registration based on expectation conditional maximization. Proc SPIE 2011 March 3, 2011;7964(1):79642Z

2D-3D Registration

- Generate digitally reconstructed radiographs (DRR)
  - Various similarity metrics exist, such as gradient information or mutual information
  - Optimize registration using a stochastic search algorithm

Otake Y, Armand M, Armiger R, Kutzer M, Basafa E, Kazanzides P, Taylor R. Intraoperative image based multi-view 2D/3D registration for image-guided orthopaedic surgery: Incorporation of fiducial-based C-arm tracking and GPU-acceleration. Medical Imaging, IEEE Transactions on 2011.

Plan Verification and Update



Surface mesh of acetabulum oriented to achieve minimum peak pressure

- Existing BGS software will update & display:
  - biomechanical data
  - radiographic angles
- Surgeon may repeat reorientation procedure to achieve optimum femoral head coverage and reduction in joint pressure

Deliverables

Minimum

1. Delineate a novel **surgical pipeline** for x-ray guided hip osteotomy
2. Optimize BB placement and develop method for firmly **attaching BBs** to bone.
3. Experimentally compare x-ray navigation method with BGS method on **pelvic phantom**

Deliverables

Expected

1. **Integrate** x-ray navigation software with existing software (BGS)
2. Experimentally compare x-ray navigation method with BGS method on a **cadaver**
3. Investigate **non-rigid attachment of FTRAC**

Deliverables

Maximum

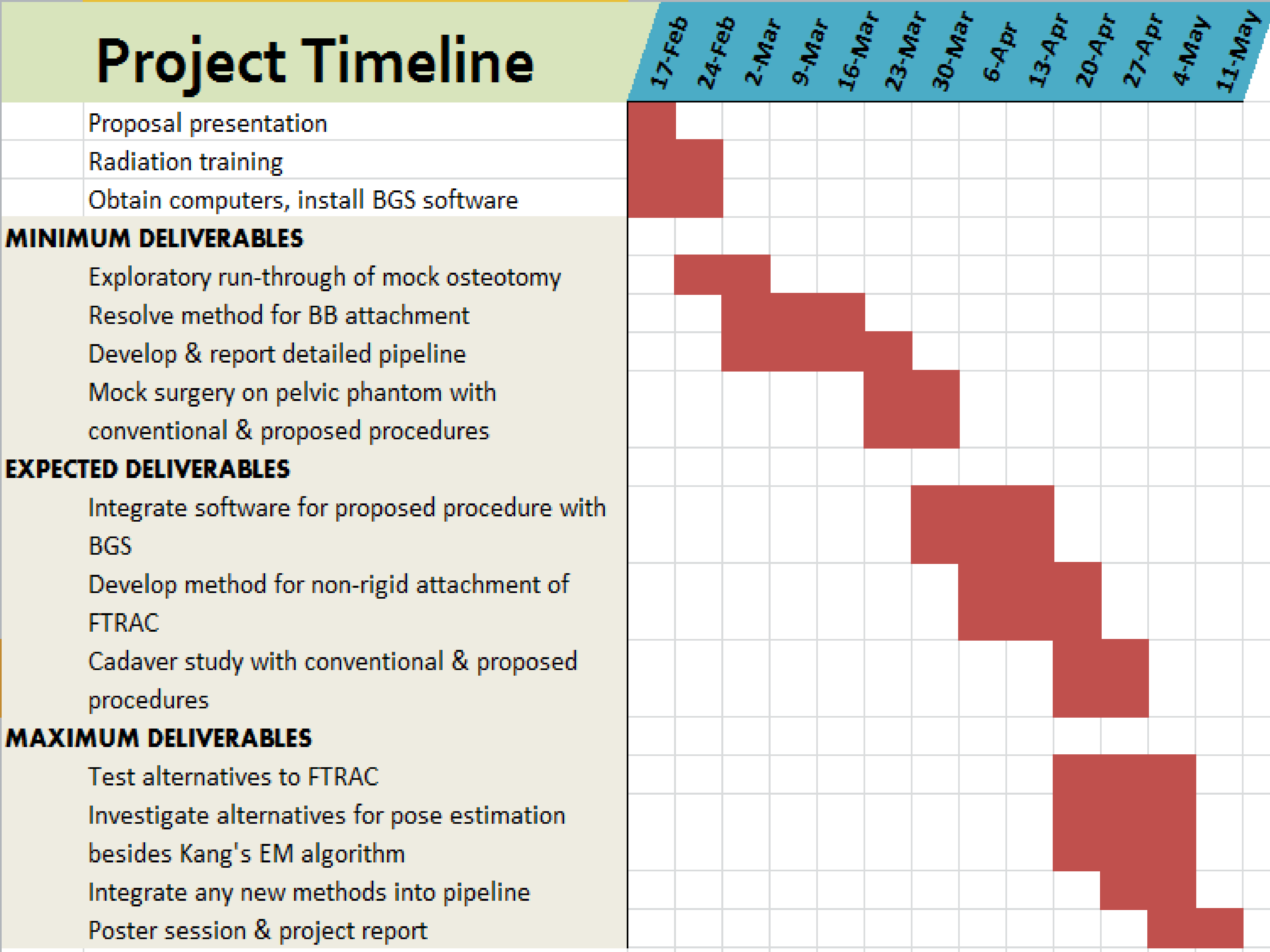
1. Investigate **automatic initialization** of ECM pose estimation algorithm
2. Investigate **alternatives to FTRAC**

3. Investigate PCA-based distortion correction

Dependencies

Status	Target Date	Description
✓	DONE	Obtain access to mock OR.
✓	DONE	Agree on weekly meeting time with mentors.
⌛	FEB 23	Radiation training from Dr. Granlund to operate C-arm.
⌛	MAR 2	Obtain computers capable of running BGS software. Portable computers that can be brought into mock OR desired but not necessary.
⌛	MAR 2	BGS software and sample data sets must be installed on the machines we use.

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												🟥	🟥

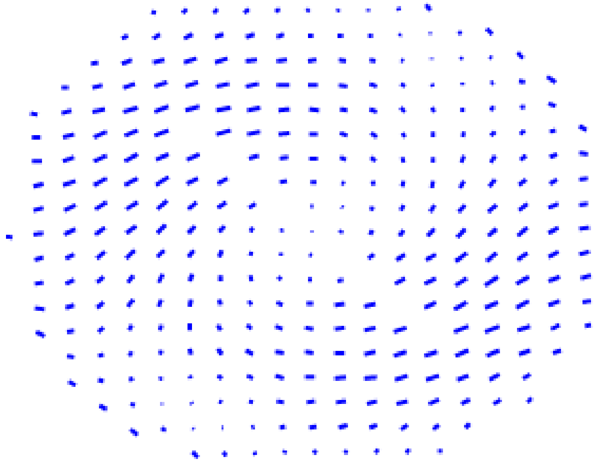
Reading List

1. The RSA Method [Internet]; c2009 [cited 2012 February 21]. Available from: www.rsabiomedical.se/umrsa/method.php.
2. Armand M, Lepisto J, Tallroth K, Elias J, Chao E. Outcome of periacetabular disease. Acta Ortho 2005;76(3):303-13.
3. Armiger RS, Armand M, Lepisto J, Minhas D, Tallroth K, Mears SC, Waites MD. Evaluation of a computerized measurement technique for joint alignment before and during periacetabular osteotomy. Computer Aided Surgery 2007;12(4):215-24.
4. Armiger RS, Armand M, Tallroth K, Lepisto J, Mears SC. Three-dimensional mechanical evaluation of joint contact pressure in 12 periacetabular osteotomy patients with 10-year follow-up. Acta Orthopaedica 2009 04;80(2):155-61.
5. Chintalapani G, Jain AK, Taylor RH. Statistical characterization of C-arm distortion with application to intra-operative distortion correction. Proc SPIE 2007;6509:65092Y.
6. David P, Dementhon D, Duraiswami R, Samet H. SoftPOSIT: Simultaneous pose and correspondence determination. International Journal of Computer Vision 2004 09/15;59(3):259-84.
7. Dementhon DF, Davis LS. Model-based object pose in 25 lines of code. International Journal of Computer Vision 1995;15(1):123-41.
8. Jain AK, Mustafa T, Zhou Y, Burdette C, Chirikjian GS, Fichtinger G. FTRAC---A robust fluoroscope tracking fiducial. Med Phys 2005 October 2005;32(10):3185-98.
9. Kang X, Taylor RH, Armand M, Otake Y, Yau WP, Cheung PYS, Hu Y. Correspondenceless 3D-2D registration based on expectation conditional maximization. Proc SPIE 2011 March 3, 2011;7964(1):79642Z.
10. Millis MB, Murphy SB. Osteotomies of the hip in the prevention and treatment of osteoarthritis. The Journal of Bone & Joint Surgery 1995;41:626-47.
11. Murphy RJ. Development and enhancement of computer-assisted hip surgeries for periacetabular osteotomy and femoracetabular impingement. Johns Hopkins University; 2010. 76 p.
12. Otake Y, Armand M, Armiger R, Kutzer M, Basafa E, Kazanzides P, Taylor R. Intraoperative image-based multi-view 2D/3D registration for image-guided orthopaedic surgery: Incorporation of fiducial-based C-arm tracking and GPU-acceleration. Medical Imaging, IEEE Transactions on 2011;PP(99).

Distortion Correction

Ambitious Solution: **PCA-based correction**

- Fix roughly 15 BBs to detector periphery
- Use PCA to recover pose-dependent distortion maps
- Drawback: need to manufacture BB phantom



(d) $+3\sigma_3 Mode3$

Sometimes eigenmodes correspond to recognizable forms of distortion, such as **spiral distortion**!

Chintalapani G, Jain AK, Taylor RH. Statistical characterization of C-arm distortion with application to intra-operative distortion correction. Proc SPIE 2007;6509:65092Y.

Distortion Correction

Step 1: Acquire prior data

Segment bead positions

Find Bernstein polynomial coefficients that minimize least squares error

Vectorize distortion maps from all images into one data matrix

Subtract mean from data matrix

Extract eigenmodes by PCA

repeat for all images in dataset

Step 2: Recover distortion map intra-operatively

- Attach BB phantom to detector periphery
- Optimize mode weights (e.g. downhill Simplex)
- Construct distortion map <u>for that pose</u>

mean distortion map

mode weights

eigenmodes

$$\triangle \vec{d} = M_0 + \sum_{i=1}^{n} \lambda_i D_i$$

recovered distortion map