Fluoroscopic Navigation for Robot-Assisted Orthopedic Surgery

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C-arm Fluoroscopy for Orthopedic Surgery

C-arm is a commonly used machine in most orthopedic operating rooms

- X-ray imaging is fast, low-cost, supplies in-depth structures of the patient anatomy
- Consecutive fluoroscopic shots present intraoperative structure changes

Goal: Guide the surgeon to operate the surgical tool and evaluate the performance

Philips Zenition C-arm platform[1]

[1] Image from: https://www.philips.com/a-w/about/news

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Fluoroscopic Guidance Challenges

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3D information is collapsed in X-ray projective imaging

- The clinicians estimate the critical 3D information through "mentally mapping"
  - Intraoperative tool-to-tissue relationship
  - Relationship with respect to pre-operative planning

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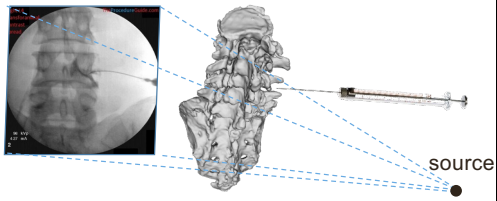
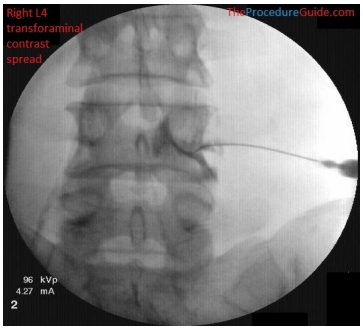
Failed estimations can lead to large operation errors



X-ray Transmission Imaging Illustration



Example Spine Needle Injection X-ray[2]

[2] X-ray image from https://theprocedureguide.com/fluoroscopic-guided-thoracic-lumbar-transforaminal-epidural-steroid-injection/

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Robot-Assisted Orthopedic Surgery

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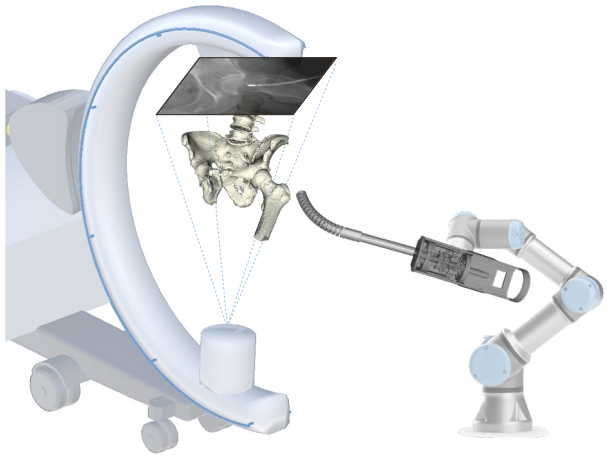
Robotic Surgical System

- Better precision, more stable, safer than human's freehand
- Automates the control of more complicated surgical tools

Navigation system is critical

- Quantitatively computes 3D tool to tissue relationship
- Navigates the robotic surgical tool to planning positions



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Concept of Fluoroscopic Navigation System

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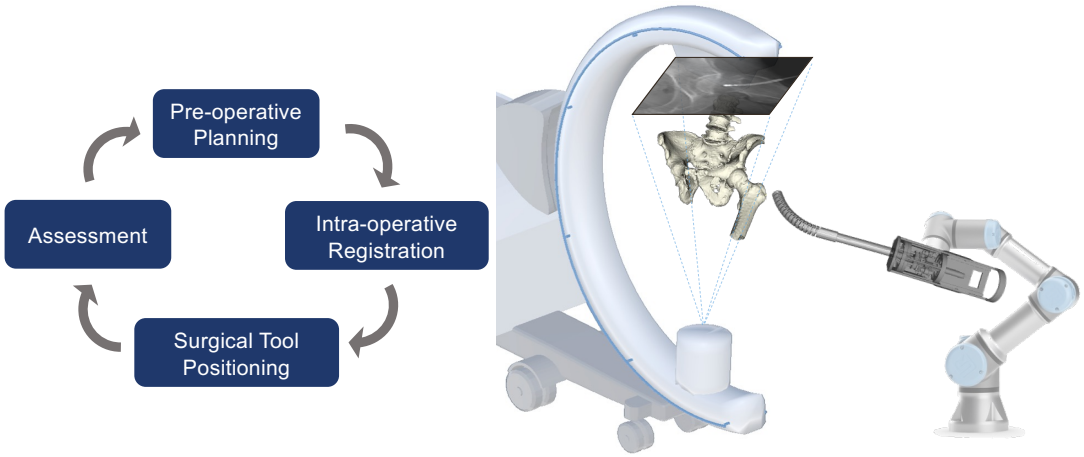

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Concept of Fluoroscopic Navigation System

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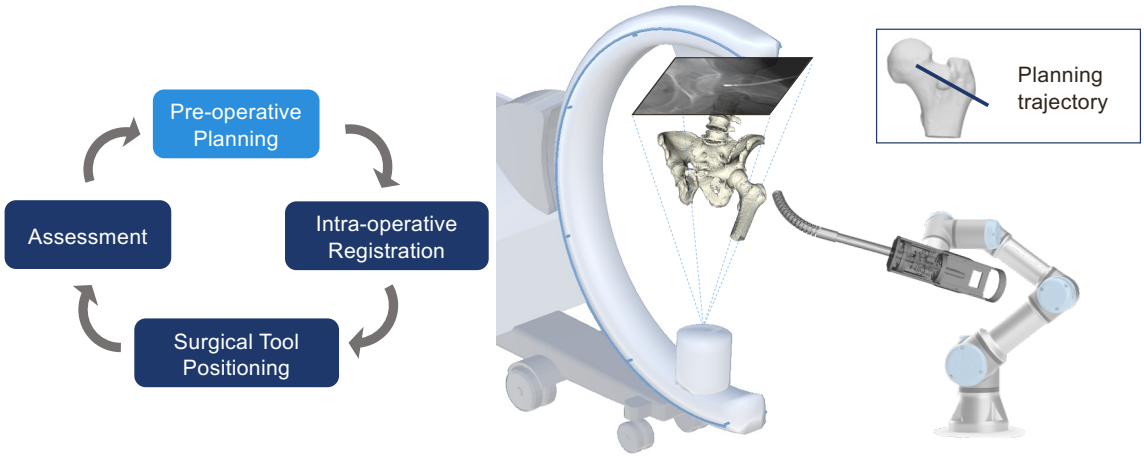

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Concept of Fluoroscopic Navigation System

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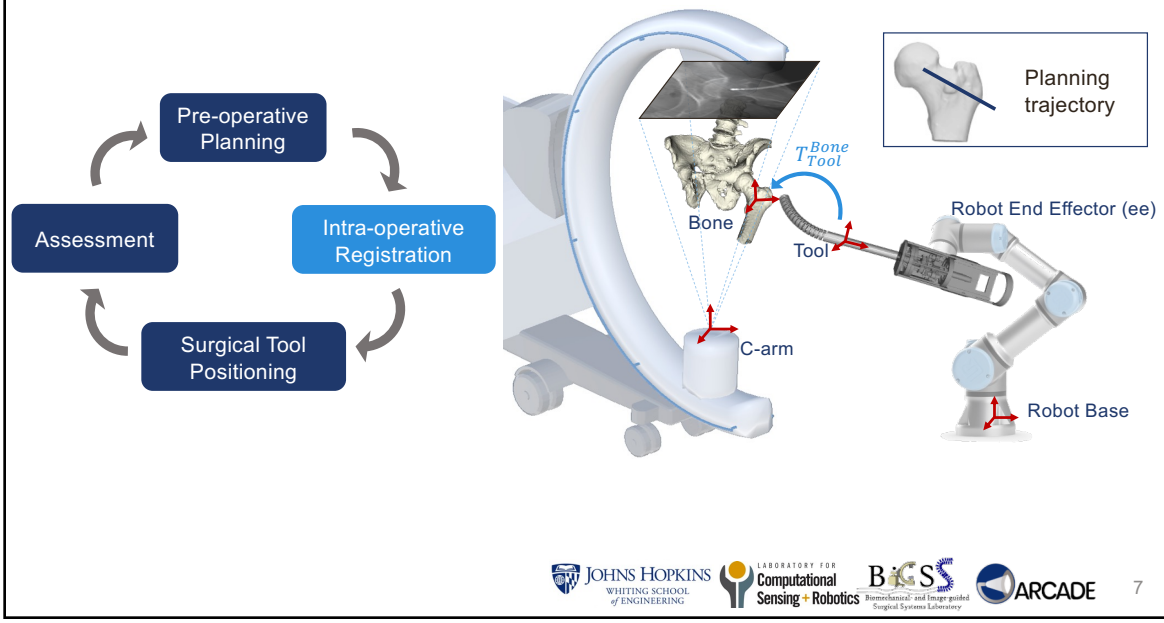

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Concept of Fluoroscopic Navigation System

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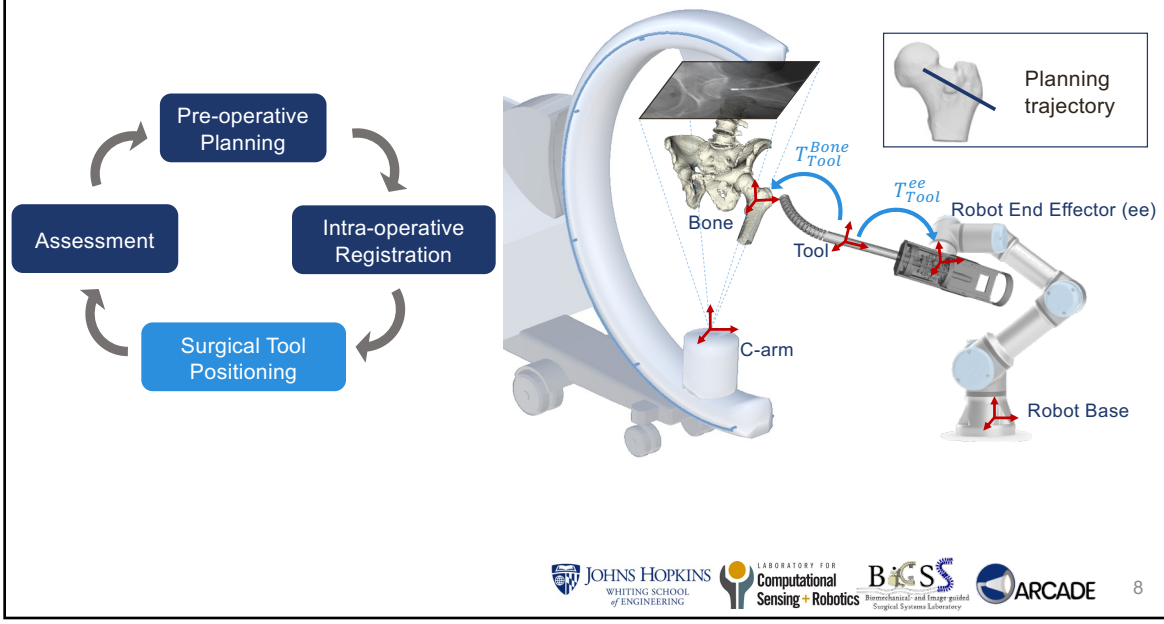

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Concept of Fluoroscopic Navigation System

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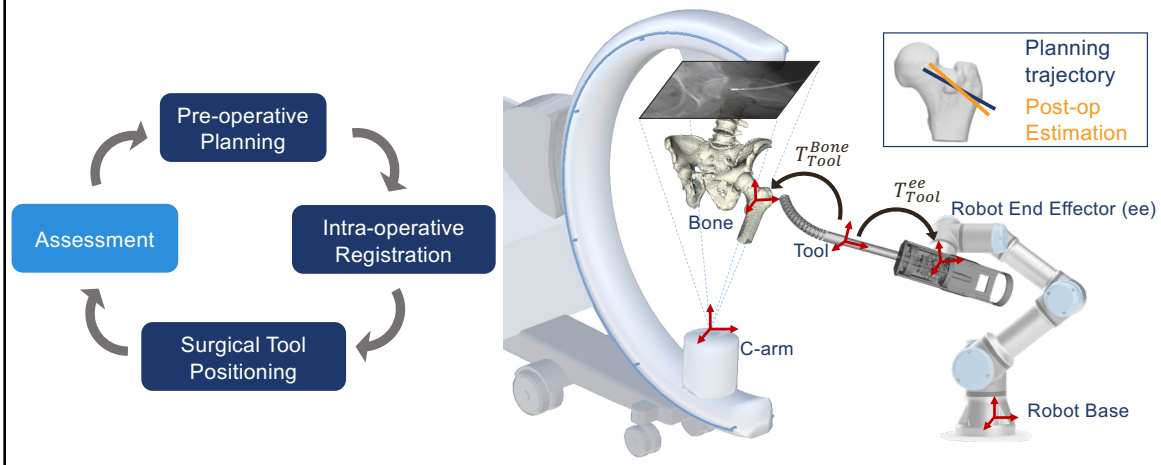

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Concept of Fluoroscopic Navigation System

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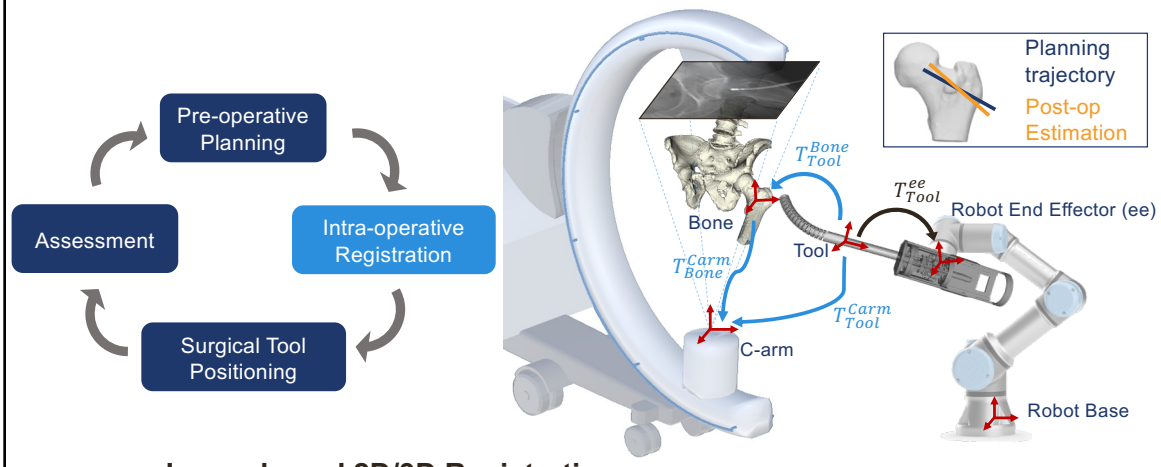

Image-based 2D/3D Registration

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Intra-operative Registration Fundamentals

2D/3D Registration

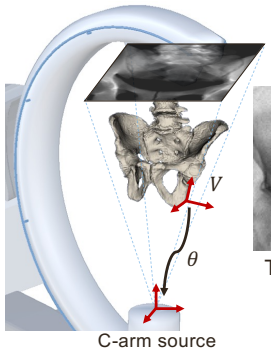
Given the following:
- 2D target image I_t
- 3D volume V
- pose parameter $\theta \in \mathrm{SE}(3)$
- a Digitally Reconstructed Radiography (DRR) operator P
- a similarity function S

2D/3D Registration solves the following optimization:

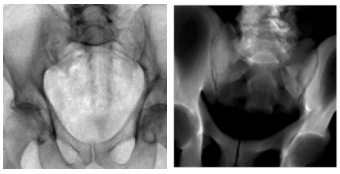
$$\theta = \min_{\theta} S(I_t, P(V;\theta))$$

When generalizing to multiple m objects and n images, including pose regularization term R:

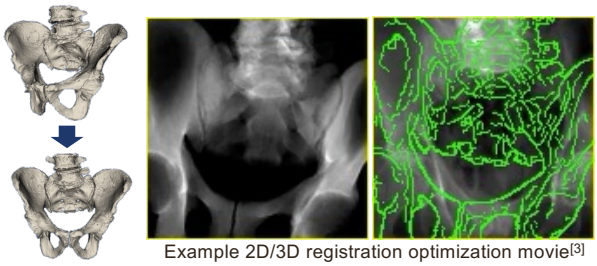
$$\{\theta_m\} = \min_{\theta_m} \sum_{n=0}^{N} S(I_n, P(V_m;\theta_m)) + R(\theta_m)$$
$$m \in \{0,..,M\}, n \in \{0,..,N\}$$



C-arm source


Target X-ray I_t DRR $P(V;\theta)$

Similarity function S


Example 2D/3D registration optimization movie[3]

[3] Generated using open-source software: xreg https://github.com/re2/xreg

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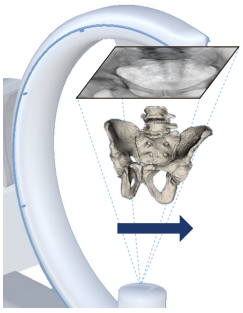
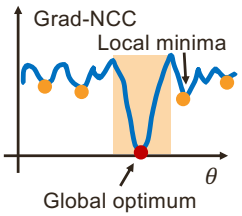
Challenges

2D/3D Registration Challenges

Narrow Capture Range

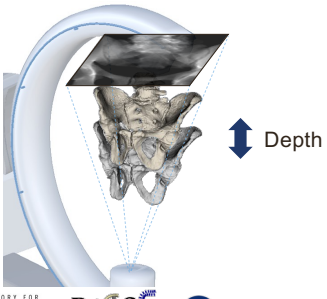
- Local minima of conventional hand-crafted similarity function, such as Gradient Normalized Cross Correlation (Grad-NCC)
- Requires the initialization close to the ground truth





Ambiguity

- Single-view registration is ambiguous along depth direction due to collapsed information in projective geometry
- More serious if the search space is more complex, such as deformable registration



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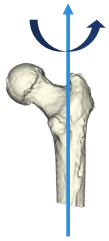
Challenges

Bone Anatomy Registration Challenges:

Example X-ray[4]

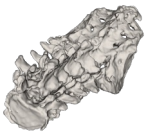
Proximal Femur

- Lack of distinct features in X-ray image
- Ambiguous in axial rotation



Spine Vertebrae

- Multi-component, size is smaller
- Shape deforms intra-operatively



[4] X-ray image resources:
https://radiopaedia.org/cases/normal-ap-lumbar-spine
Chiamil, Sara Muñoz, and Claudia Astudillo Abarca. "Imaging of the hip: a systematic approach to the young adult hip." Muscles, Ligaments and Tendons Journal 6.3 (2016): 265.

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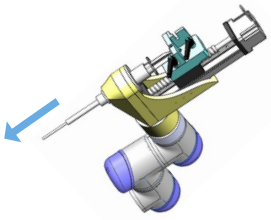
Challenges

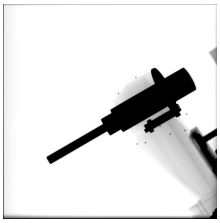
Surgical Tool Registration Challenges:

Example X-ray

Rigid Bone Drilling & Injection Device[5]

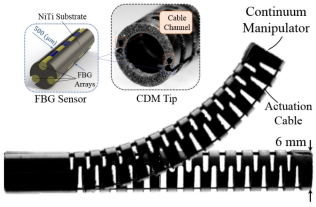
- Metallic guide is symmetric, no texture under X-ray
- Orientation accuracy is critical

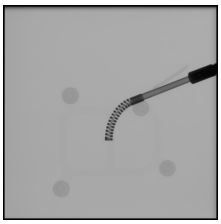




Dexterous Continuum Manipulator[6]

- Small and flexible
- Shape estimation is critical





[5] Bakhtiarinejad, M., Gao, C., Farvardin, A., Zhu, G., Yu, W., Oni, J., Taylor, R.H. and Armand, M., 2022. A Surgical Robotic System for Osteoporotic Hip Augmentation: An Early feasibility study. Under Review of TMRB
[6] Sefati, S., Hegeman, R., Alambeigi, F., Iordachita, I., Kazanzides, P., Khanuja, H., Taylor, R.H. and Armand, M., 2020. A surgical robotic system for treatment of pelvic osteolysis using an FBG-equipped continuum manipulator and flexible instruments. IEEE/ASME Transactions on Mechatronics, 26(1), pp.369-380.

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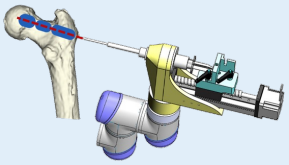
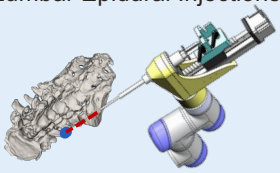
Outline

Part I: Clinical Application Developments

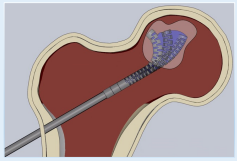
Femoroplasty



Lumbar Epidural Injections

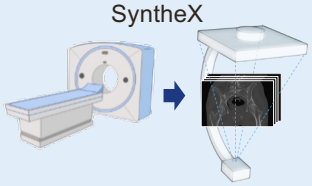


Core Decompression

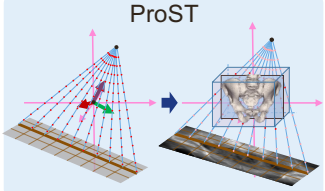


Part II: Machine Learning Investigations

SyntheX



ProST



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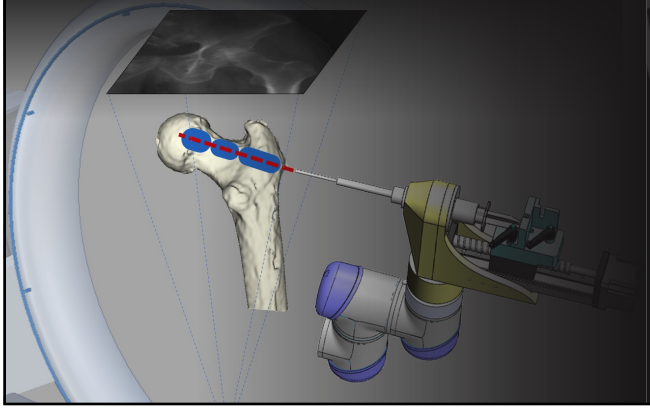
Part I – Clinical Application Developments

Femoroplasty



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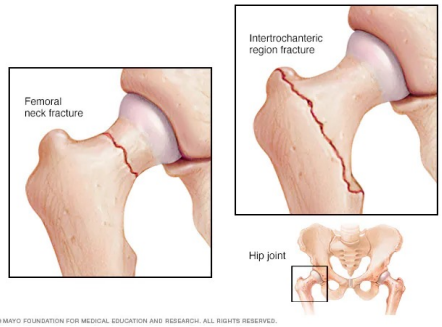
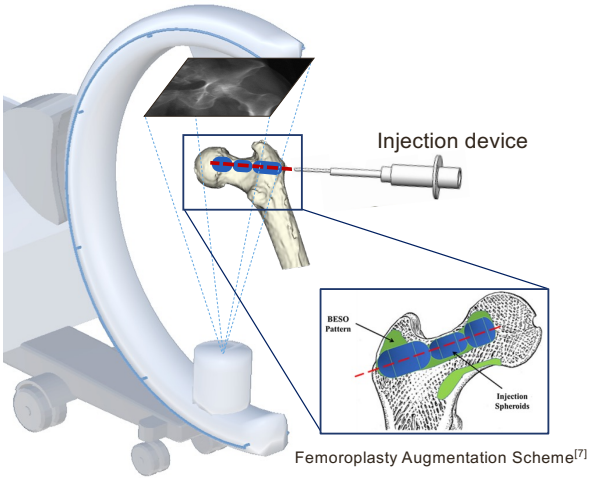
Clinical Background

Femoroplasty

- A preventive therapeutic procedure proposed for patients with osteoporosis
- Inject bone cement to an osteoporotic femur to reduce the risk of fracture





Femoroplasty Augmentation Scheme[7]

[7] Farvardin, A., Basafa, E., Bakhtiarinejad, M., & Armand, M. (2019). Significance of preoperative planning for prophylactic augmentation of osteoporotic hip: A computational modeling study. Journal of biomechanics, 94, 75-81.

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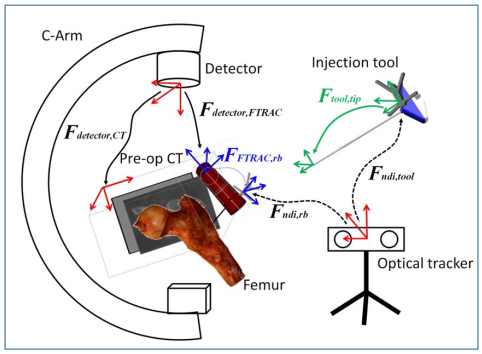
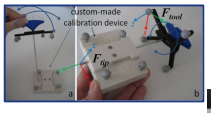
Previous Efforts: Hand-held Injection

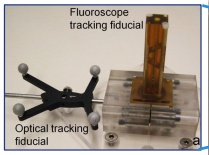
Fiducial-based Navigation



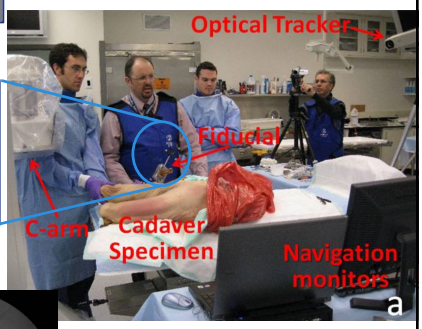
Fiducial-based Femoroplasty System Configuration[8][9]



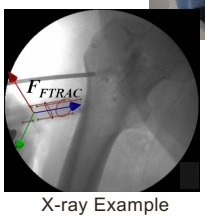
Tool Fiducial



Bone Fiducial



Hand-held Cadaver Injection Study[9]



X-ray Example

[8] Otake, Y., Armand, M., Sadowsky, O., Armiger, R. S., Kutzer, M. D., Mears, S. C., ... & Taylor, R. H. (2010, February). An image-guided femoroplasty system: development and initial cadaver studies. In Medical Imaging 2010: Visualization, Image-Guided Procedures, and Modeling (Vol. 7625, p. 76250P). International Society for Optics and Photonics.

[9] Otake, Y., Armand, M., Armiger, R. S., Kutzer, M. D., Basafa, E., Kazanzides, P., & Taylor, R. H. (2011). Intraoperative image-based multiview 2D/3D registration for image-guided orthopaedic surgery: incorporation of fiducial-based C-arm tracking and GPU-acceleration. IEEE transactions on medical imaging, 31(4), 948-962.

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Previous Efforts: Hand-held Injection

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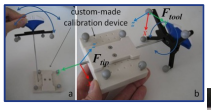
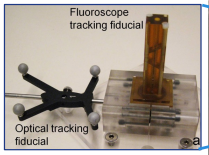
Fiducial-based Navigation

Limitations:

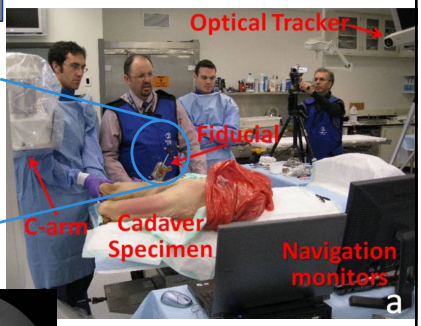
- Bone pin fiducial introduces additional incision to the patient
- Hand-held drilling is not stable
- X-ray field-of-view is limited to capture all fiducials



Tool Fiducial



Bone Fiducial



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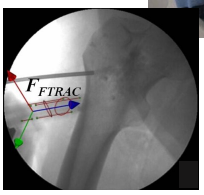

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[8] Otake, Y., Armand, M., Sadowsky, O., Armiger, R. S., Kutzer, M. D., Mears, S. C., ... & Taylor, R. H. (2010, February). An image-guided femoroplasty system: development and initial cadaver studies. In Medical Imaging 2010: Visualization, Image-Guided Procedures, and Modeling (Vol. 7625, p. 76250P). International Society for Optics and Photonics.
[9] Otake, Y., Armand, M., Armiger, R. S., Kutzer, M. D., Basafa, E., Kazanzides, P., & Taylor, R. H. (2011). Intraoperative image-based multiview 2D/3D registration for image-guided orthopaedic surgery: incorporation of fiducial-based C-arm tracking and GPU-acceleration. IEEE transactions on medical imaging, 31(4), 948-962.

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Robot-Assisted Femoroplasty

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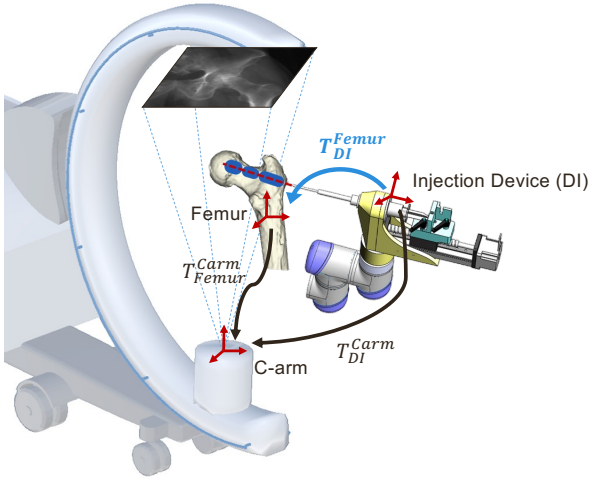
Proposed Objectives

Robotic Drilling/Injection

- UR-10 as a steady positioning robot arm

Fiducial-free Navigation

- Use purely C-arm X-ray images to estimate the critical T_{DI}^{Femur}



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Navigation Pipeline for Robot-Assisted Femoroplasty

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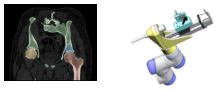
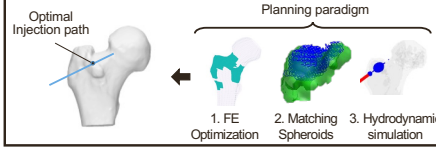
Inputs
Patient CT
Femur Segmentation
Drilling/Injection Device Model

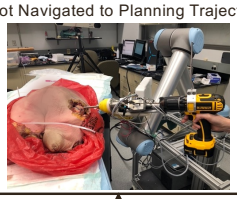


Preoperative CT scan → Femur segmentation → Finite element model

Planning paradigm

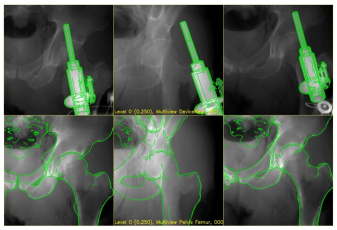


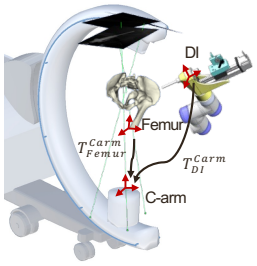
Robot Navigated to Planning Trajectory



→ **Femoroplasty Performed**

Estimate Femur and Robot Pose with Intensity-Based 2D/3D Registration





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Navigation Pipeline for Robot-Assisted Femoroplasty

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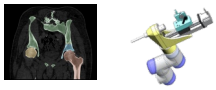
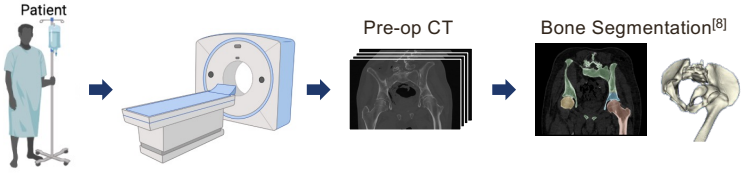
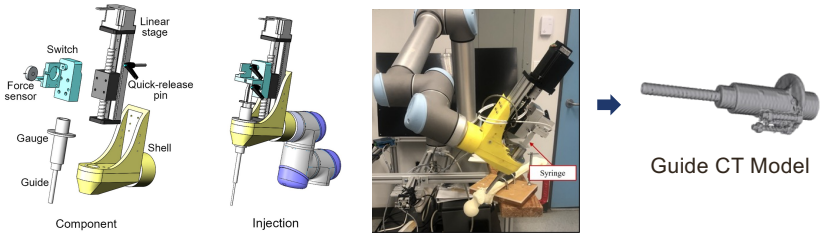
Inputs
Patient CT
Femur Segmentation
Drilling/Injection Device Model



Patient-Specific CT Scans and Bone Segmentation



Custom-Designed Bone Drilling & Injection Device[5]



Credit: Designed by Mahsan Bakhtiarinejad and Dr. Amir Farvardin

[8] Krčah, M., Székely, G. and Blanc, R., 2011, March. Fully automatic and fast segmentation of the femur bone from 3D-CT images with no shape prior. In 2011 IEEE international symposium on biomedical imaging: from nano to macro (pp. 2087-2090). IEEE.
[5] Bakhtiarinejad, M., Gao, C., Farvardin, A., Zhu, G., Yu, W., Oni, J., Taylor, R.H. and Armand M., 2022. A Surgical Robotic System for Osteoporotic Hip Augmentation: An Early feasibility study. Under Review of TMRB

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Overall Femoroplasty Navigation Pipeline

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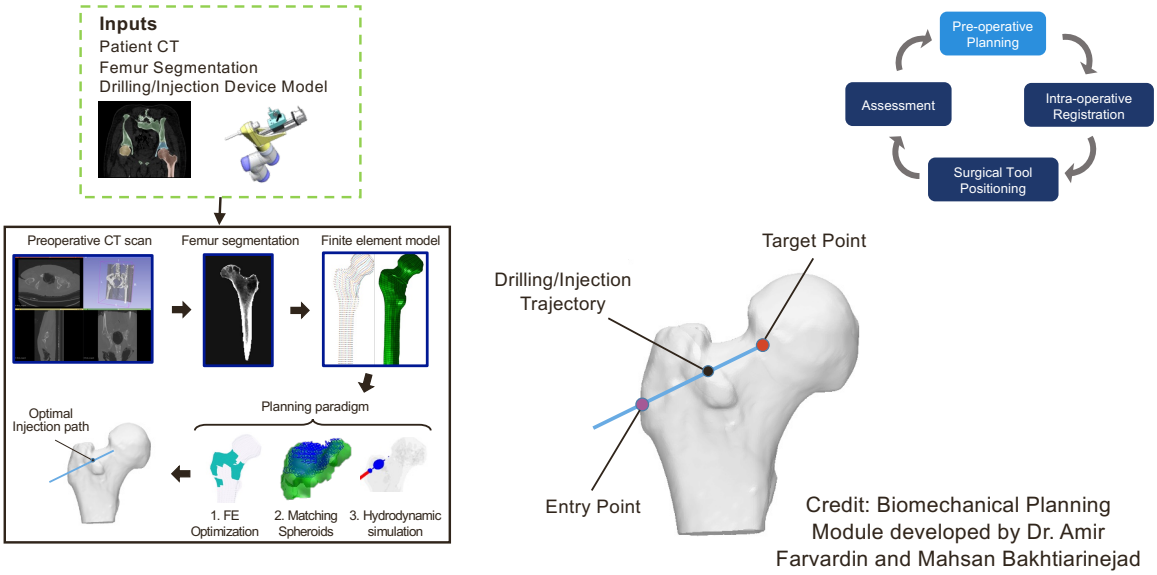

[7] Farvardin, A., Basafa, E., Bakhtiarinejad, M., & Armand, M. (2019). Significance of preoperative planning for prophylactic augmentation of osteoporotic hip: A computational modeling study. Journal of biomechanics, 94, 75-81.

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Overall Femoroplasty Navigation Pipeline

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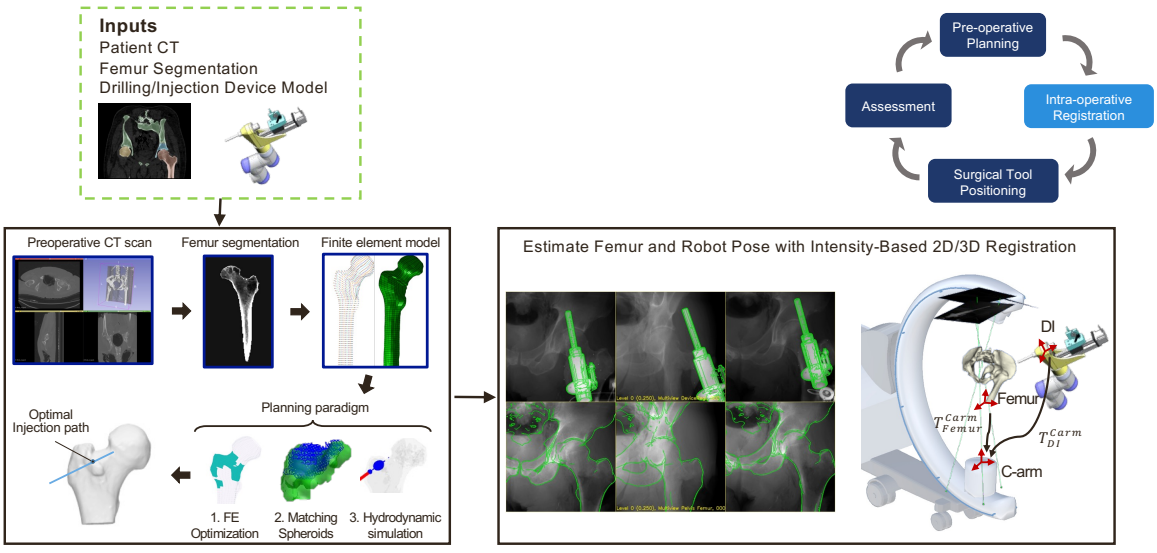

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Registration Methods

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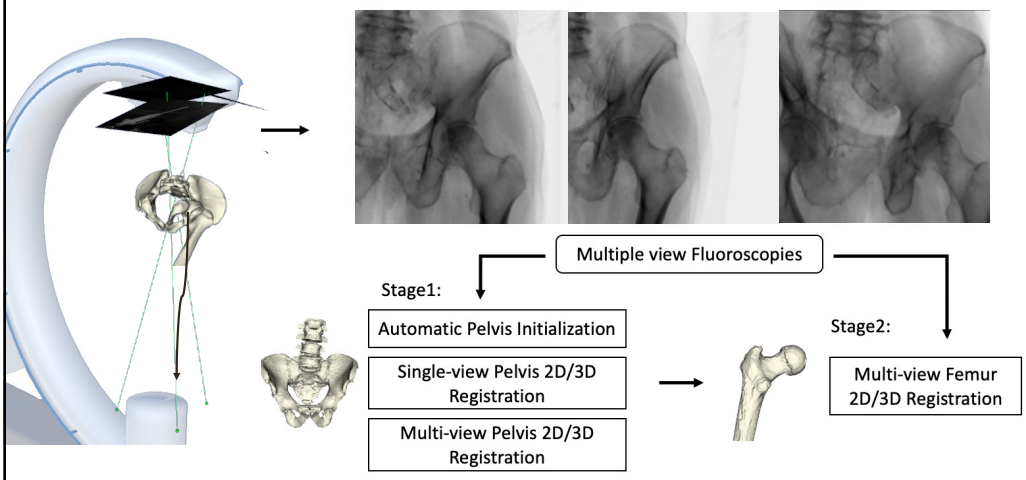
Femur Registration Pipeline



[9] **Gao, C.**, Grupp, R. B., Unberath, M., Taylor, R. H., & Armand, M. (2020, March). Fiducial-free 2D/3D registration of the proximal femur for robot-assisted femoroplasty. In Medical Imaging 2020: Image-Guided Procedures, Robotic Interventions, and Modeling (Vol. 11315, p. 113151C). International Society for Optics and Photonics.

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Registration Methods

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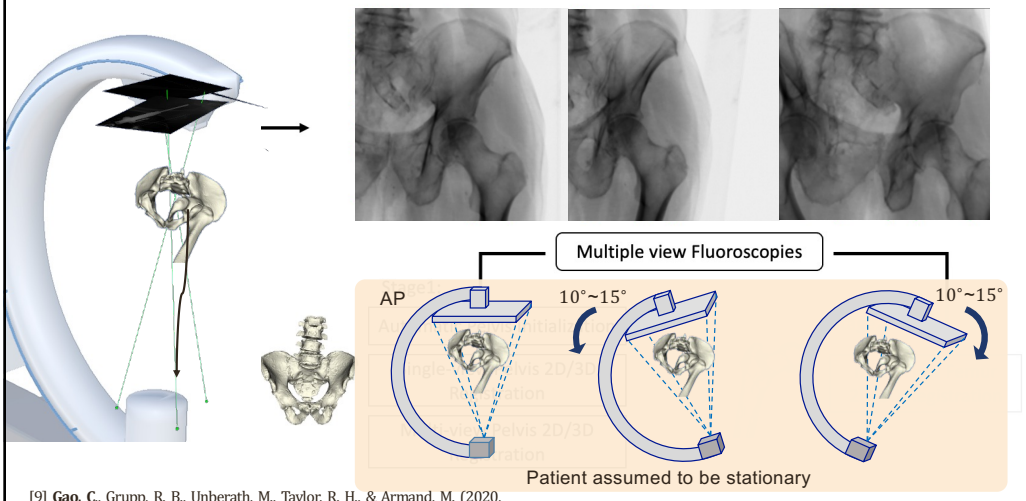
Multi-view Data Acquisition



[9] **Gao, C.**, Grupp, R. B., Unberath, M., Taylor, R. H., & Armand, M. (2020, March). Fiducial-free 2D/3D registration of the proximal femur for robot-assisted femoroplasty. In Medical Imaging 2020: Image-Guided Procedures, Robotic Interventions, and Modeling (Vol. 11315, p. 113151C). International Society for Optics and Photonics.

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Registration Methods

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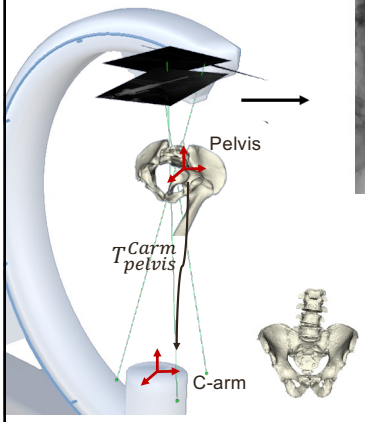
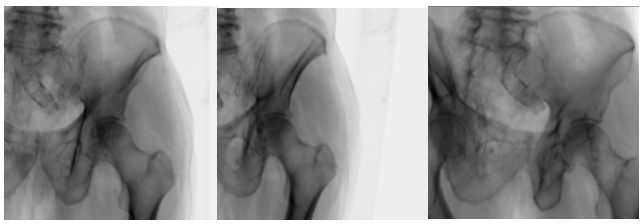
Pelvis Registration





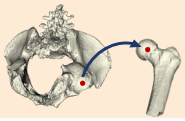
Multiple view Fluoroscopies

Stage1:

- Automatic Pelvis Initialization
- Single-view Pelvis 2D/3D Registration
- Multi-view Pelvis 2D/3D Registration

Reason:

- Pelvis registration is more accurate than femur [11], because it is bigger and has more textures
- Pelvis registration estimates multi-view C-arm geometry
- Initialize and regularize femur registration



[11] Grupp, R.B., Hegeman, R.A., Murphy, R.J., Alexander, C.P., Otake, Y., McArthur, B.A., Armand, M. and Taylor, R.H., 2019. Pose estimation of periacetabular osteotomy fragments with intraoperative X-ray navigation. IEEE Transactions on Biomedical Engineering, 67(2), pp.441-452.

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Registration Methods

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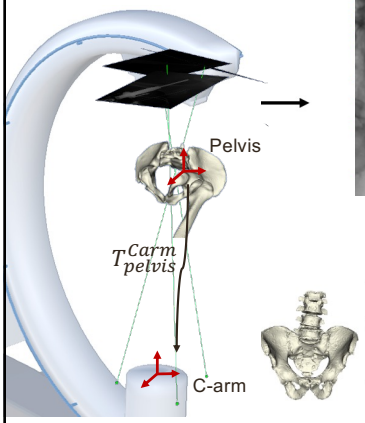
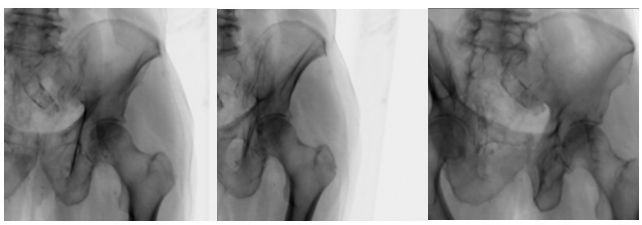
Pelvis Registration



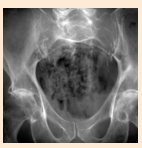


Multiple view Fluoroscopies

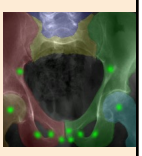
Stage1:

- Automatic Pelvis Initialization
- Single-view Pelvis 2D/3D Registration
- Multi-view Pelvis 2D/3D Registration

Automatic Initialization



Concurrent Segmentation and Localization[*]



Solve a PnP problem using corresponding landmarks

[10] Grupp, R.B., Unberath, M., **Gao, C.**, Hegeman, R.A., Murphy, R.J., Alexander, C.P., Otake, Y., McArthur, B.A., Armand, M. and Taylor, R.H., 2020. Automatic annotation of hip anatomy in fluoroscopy for robust and efficient 2D/3D registration. International journal of computer assisted radiology and surgery, 15(5), pp.759-769.

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Registration Methods

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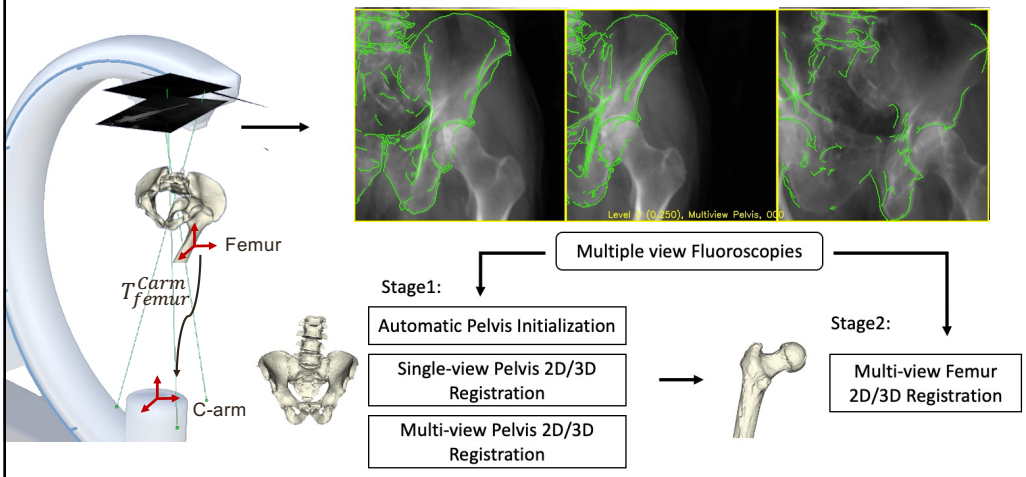
Femur Registration



[9] **Gao, C.**, Grupp, R. B., Unberath, M., Taylor, R. H., & Armand, M. (2020, March). Fiducial-free 2D/3D registration of the proximal femur for robot-assisted femoroplasty. In Medical Imaging 2020: Image-Guided Procedures, Robotic Interventions, and Modeling (Vol. 11315, p. 113151C). International Society for Optics and Photonics.

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Registration Methods

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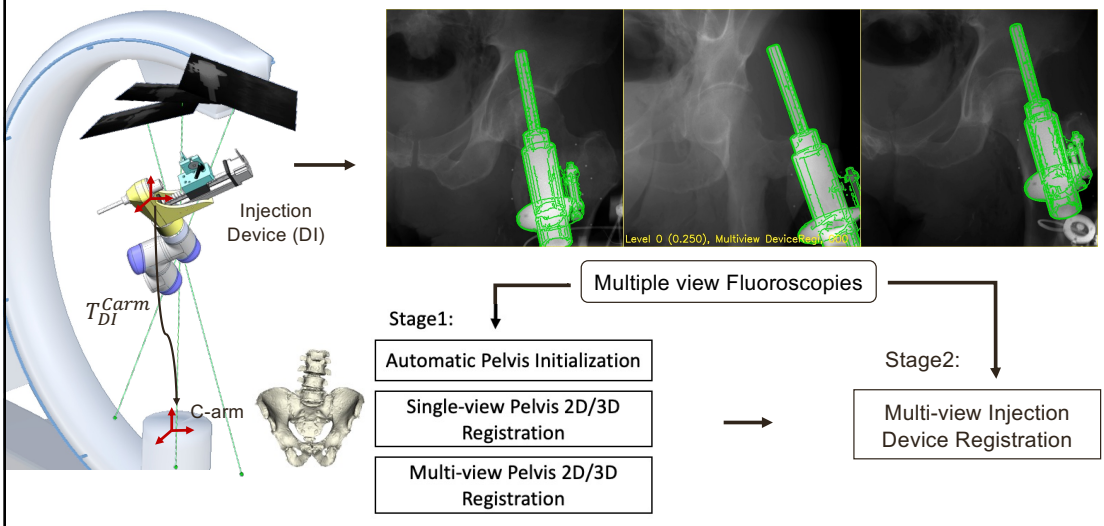
Injection Device Registration



[12] **Gao, C.**, Farvardin, A., Grupp, R.B., Bakhtiarinejad, M., Ma, L., Thies, M., Unberath, M., Taylor, R.H. and Armand, M., 2020. Fiducial-free 2D/3D registration for robot-assisted femoroplasty. IEEE transactions on medical robotics and bionics, 2(3), pp.437-446.

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Registration Simulation Study

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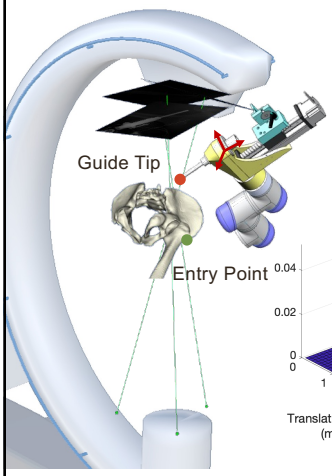
Simulated 1,000 Registrations with Randomized Geometries

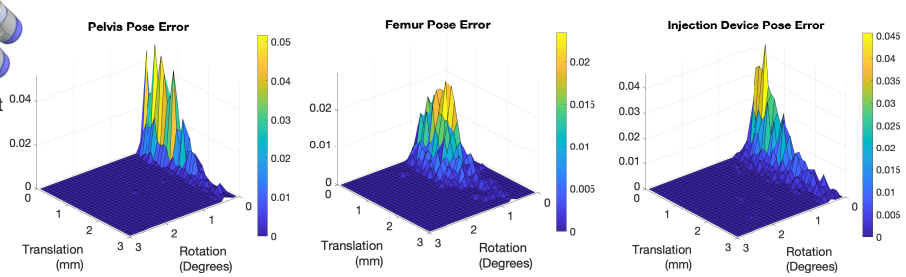
Table: Simulation Error

	mean	median
Entry Point (mm)	1.70 ± 0.94	1.64
Guide Tip (mm)	0.93 ± 0.81	0.74
Relative (mm)	1.26 ± 0.74	1.15
Femur Path (°)	0.63 ± 0.21	0.62
Guide Path (°)	0.17 ± 0.19	0.14

Femur entry point relative to Guide tip

$$Dist_{l2} = \| (P_{carm}^{FEPgt} - P_{carm}^{FEPest}) - (P_{carm}^{IDTgt} - P_{carm}^{IDTest}) \|_2$$





Joint Histogram of Translation and Rotation Errors

[12] **Gao, C.**, Farvardin, A., Grupp, R.B., Bakhtiarinejad, M., Ma, L., Thies, M., Unberath, M., Taylor, R.H. and Armand, M., 2020. Fiducial-free 2D/3D registration for robot-assisted femoroplasty. IEEE transactions on medical robotics and bionics, 2(3), pp.437-446.

Femoroplasty Registration Cadaver Experiment

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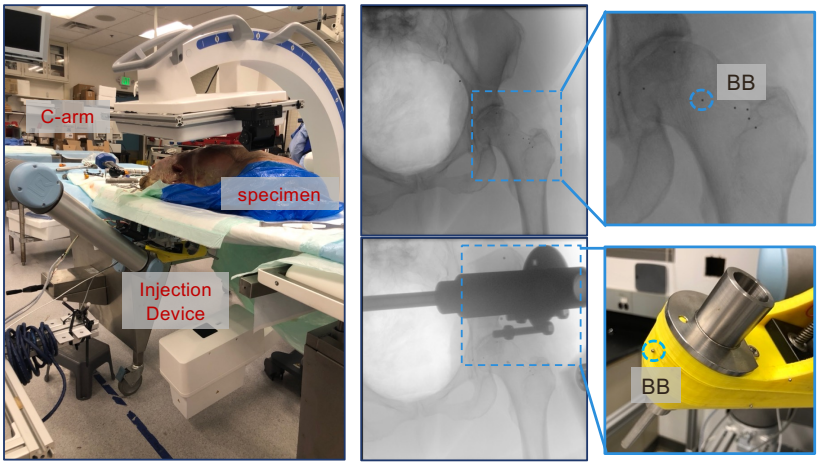
Cadaveric Experiment Setup

Ground truth pose obtained using metallic BB annotations, solving a PnP problem.



Credit: BB injection performed by Dr. Liuhong Ma

[12] **Gao, C.**, Farvardin, A., Grupp, R.B., Bakhtiarinejad, M., Ma, L., Thies, M., Unberath, M., Taylor, R.H. and Armand, M., 2020. Fiducial-free 2D/3D registration for robot-assisted femoroplasty. IEEE transactions on medical robotics and bionics, 2(3), pp.437-446.

Femoroplasty Registration Cadaver Experiment

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Cadaveric Experiment Result

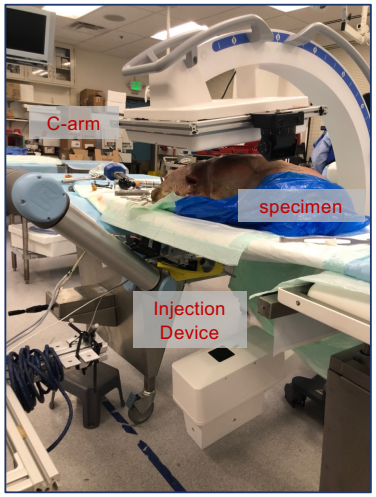


Table: Positional Registration Error of Six Individual Trials

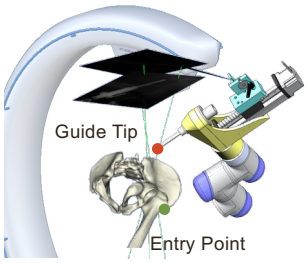
mm	Trial1	Trial2	Trial3	Trial4	Trial5	Trial6
Entry Point	1.34	2.44	2.41	1.99	3.67	4.38
Device Tip	3.17	0.84	1.48	2.93	1.79	0.83
Relative	**1.98**	**2.88**	**3.44**	**1.32**	**1.94**	**4.28**

Femur entry point relative to Guide tip

$$Dist_{l2} = \| (P_{carm}^{FEPgt} - P_{carm}^{FEPest}) - (P_{carm}^{IDTgt} - P_{carm}^{IDTest}) \|_2$$

Mean Relative Error: **2.64 ± 1.10 mm**

Clinically Acceptable Error: 2 - 3 mm



[12] **Gao, C.**, Farvardin, A., Grupp, R.B., Bakhtiarinejad, M., Ma, L., Thies, M., Unberath, M., Taylor, R.H. and Armand, M., 2020. Fiducial-free 2D/3D registration for robot-assisted femoroplasty. IEEE transactions on medical robotics and bionics, 2(3), pp.437-446.

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Overall Femoroplasty Navigation Pipeline

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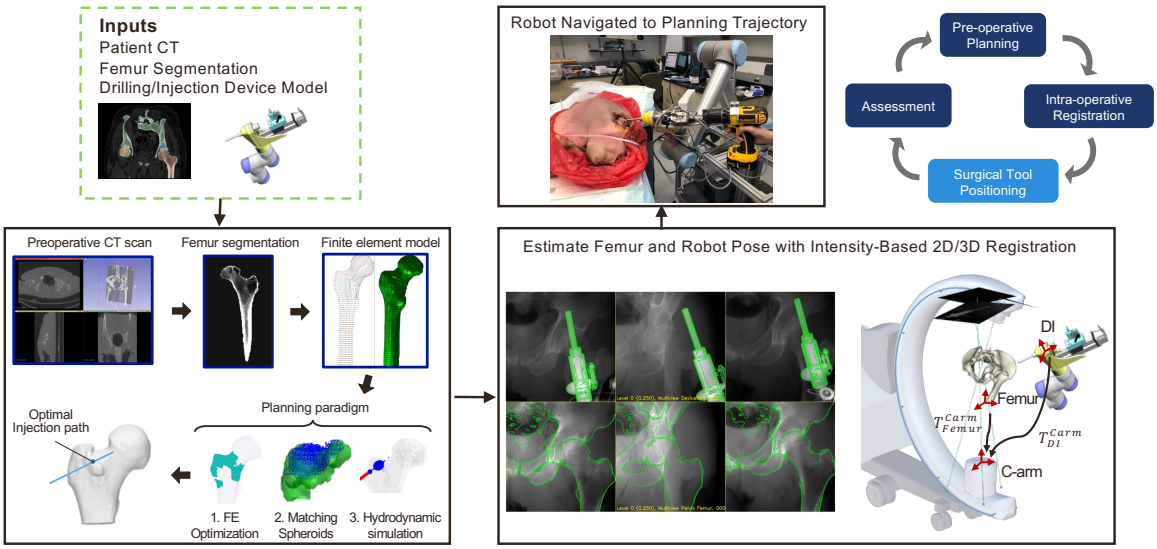

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System Calibration

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Hand-eye Calibration

- Solve an axxb problem

$$(T_{carm}^{DI})_i \cdot \boldsymbol{T_{DI}^{DF}} \cdot (T_{DF}^{SF})_i = (T_{carm}^{DI})_j \cdot \boldsymbol{T_{DI}^{DF}} \cdot (T_{DF}^{SF})_j$$

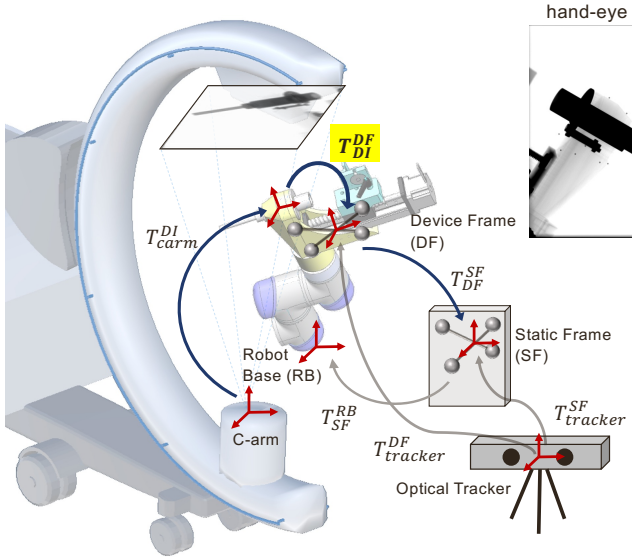
$$(T_{carm}^{DI})_j^{-1}(T_{carm}^{DI})_i \cdot \boldsymbol{T_{DI}^{DF}} = \boldsymbol{T_{DI}^{DF}} \cdot (T_{DF}^{SF})_j (T_{DF}^{SF})_i^{-1}$$

$$AX = XB$$

Note:
The tracker is used for closed-loop control, because the UR forward kinematic accuracy is insufficient for this task.

Credit: Closed-loop control module developed by Henry Phalen

Example X-ray for hand-eye calibration



[5] Bakhtiarinejad, M., **Gao, C.**, Farvardin, A., Zhu, G., Yu, W., Oni, J., Taylor, R.H. and Armand, M., 2022. A Surgical Robotic System for Osteoporotic Hip Augmentation: An Early feasibility study. Under Review of TMRB

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Femoroplasty System Integration Cadaver Experiment

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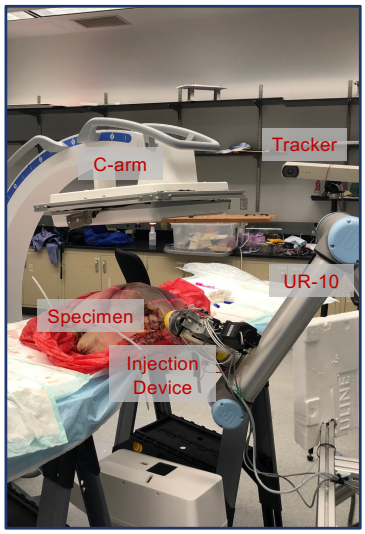
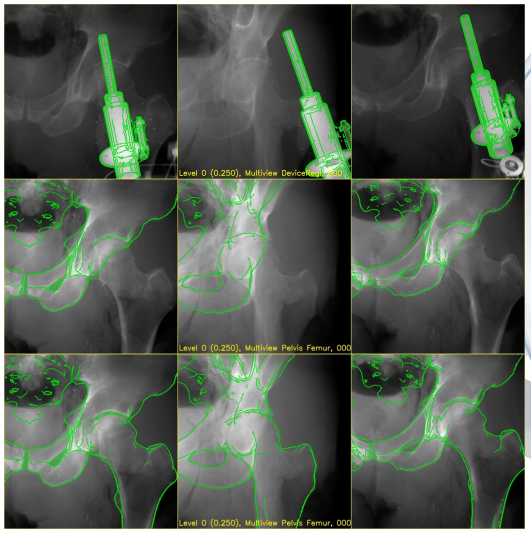
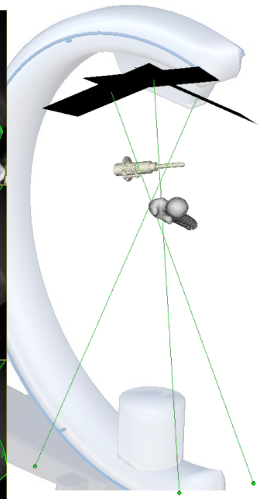
Cadaver Experiment Setup and Registration Visualizations







Multi-view Geometry

[5] Bakhtiarinejad, M., **Gao, C.**, Farvardin, A., Zhu, G., Yu, W., Oni, J., Taylor, R.H. and Armand, M., 2022. A Surgical Robotic System for Osteoporotic Hip Augmentation: An Early feasibility study. Under Review of TMRB

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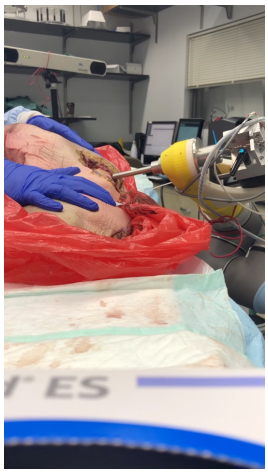
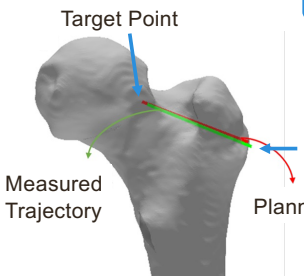
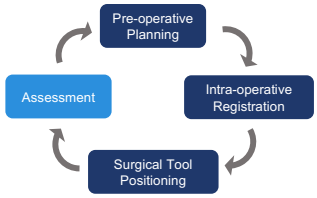
Cadaveric Drilling and Results



Drilling after the guide is positioned

Post-op CT Analysis





Target point error: 2.64 mm

Insertion point error: 3.28 mm

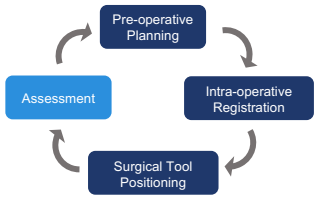
Orientation error: 2.30 degrees

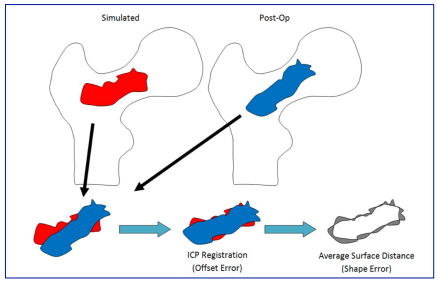
[5] Bakhtiarinejad, M., **Gao, C.**, Farvardin, A., Zhu, G., Yu, W., Oni, J., Taylor, R.H. and Armand, M., 2022. A Surgical Robotic System for Osteoporotic Hip Augmentation: An Early feasibility study. Under Review of TMRB

Clinical Evaluation

Yield load estimation with biomechanical simulation:

- **33% increase** of yield load with the measured trajectory error
- Previous biomechanical studies show **positive augmentation effects** when distance error ~8mm, rotation error ~5°[13]





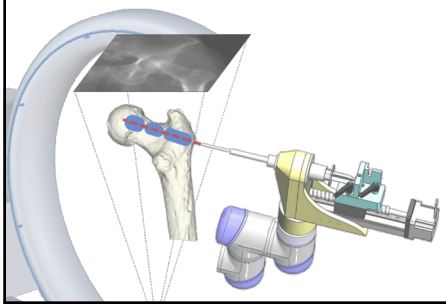
Credit: Yield load estimation performed by Mahsan Bakhtiarinejad

[5] Bakhtiarinejad, M., **Gao, C.**, Farvardin, A., Zhu, G., Yu, W., Oni, J., Taylor, R.H. and Armand, M., 2022. A Surgical Robotic System for Osteoporotic Hip Augmentation: An Early feasibility study. Under Review of TMRB

[13] Basafa, Ehsan. Computer-Assisted Femoral Augmentation For Osteoporotic Hip Fracture Prevention. Diss. Johns Hopkins University, 2013.

Conclusion and Contributions

- An automatic, intensity-based 2D/3D registration method for pose estimation of the femur
- A fiducial-free navigation pipeline for robot-assisted femoroplasty
- Evaluated the navigation methods with simulation and cadaver experiments. The results meet clinical requirements, and suggest feasibility to be used for related orthopedic applications



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Acknowledgment

Dr. Robert Grupp: Developed 2D/3D registration software infrastructure - xreg, contributed to femur registration algorithm design

Mrs. Mahsan Bakhtiarinejad and Dr. Amir Farvardin: Designed the injection unit, developed biomechanical analysis pipeline, contributed to cadaver experiments and analysis

Mr. Henry Phalen: Developed the robot closed-loop control module

Dr. Liuhong Ma and Ms. Mareike Thies: Helped with cadaver experiments

Related Publications/Manuscripts:

- **Gao, C.**, Farvardin, A., Grupp, R.B., Bakhtiarinejad, M., Ma, L., Thies, M., Unberath, M., Taylor, R.H. and Armand, M., 2020. Fiducial-free 2D/3D registration for robot-assisted femoroplasty. IEEE transactions on medical robotics and bionics, 2(3), pp.437-446.
- **Gao, C**., Grupp, R. B., Unberath, M., Taylor, R. H., & Armand, M. (2020, March). Fiducial-free 2D/3D registration of the proximal femur for robot-assisted femoroplasty. In Medical Imaging 2020: Image-Guided Procedures, Robotic Interventions, and Modeling (Vol. 11315, p. 113151C). International Society for Optics and Photonics.
- Bakhtiarinejad, M., **Gao, C.**, Farvardin, A., Zhu, G., Yu, W., Oni, J., Taylor, R.H. and Armand, M., 2022. A Surgical Robotic System for Osteoporotic Hip Augmentation: An Early feasibility study. Under Review of TMRB

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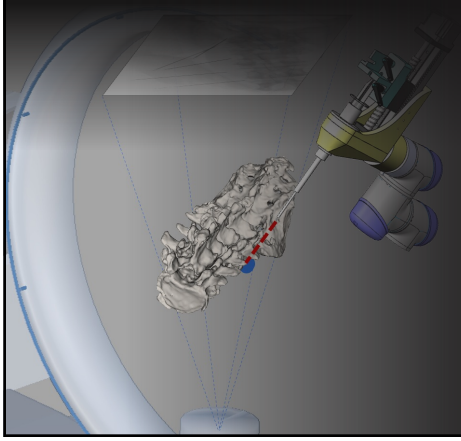
Part I – Clinical Application Developments

Lumbar Epidural Injections



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Clinical Background

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Pain Relief from Spine Epidural Injections

- Globally, between 60-80% of people are expected to experience lower back pain in lifetime
- 30 million epidural injections worldwide
- Effectiveness is highly variable (50-70% efficacy rates)
- Failed injections can result in catastrophic spinal cord of nerve root injuries, even paralysis

Example Spine Needle Injection[13]

[13] https://www.spineuniverse.com/treatments/pain-management/thoracic-epidural-injection
[14] https://orthoinfo.aaos.org/en/treatment/spinal-injections/

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Clinical Background

Clinical Practice and Challenges

The clinician acquires several fluoroscopic images before and during the manual insertion of the needle

Lack of 3D needle position estimation with respect to the spine vertebrae

Clinician's needle injection under fluoroscopic guidance[15]

[15] https://www.vapainsc.com/treatments-and-procedures/lumbar-epidural-steroid-injections%E2%80%93-transforaminal.html

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Autonomous Robotic Spinal Needle Insertion

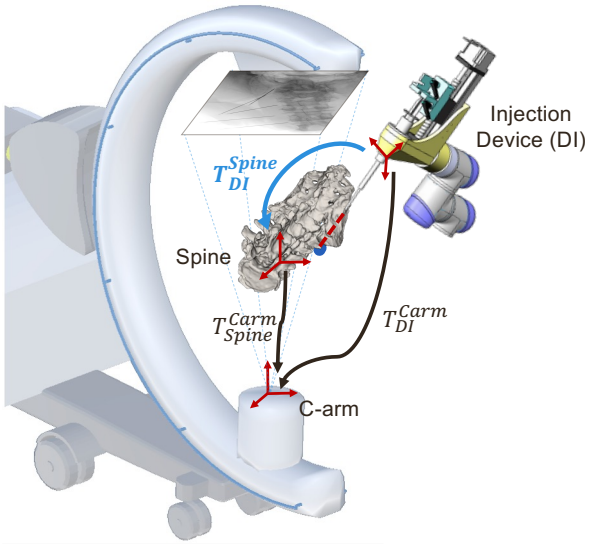
Proposed Objectives

Robotic Needle Injection

- Robotic End Effector delivers the needle

Fiducial-Free Navigation

- Use purely C-arm X-ray images to estimate the critical T_{DI}^{Spine}



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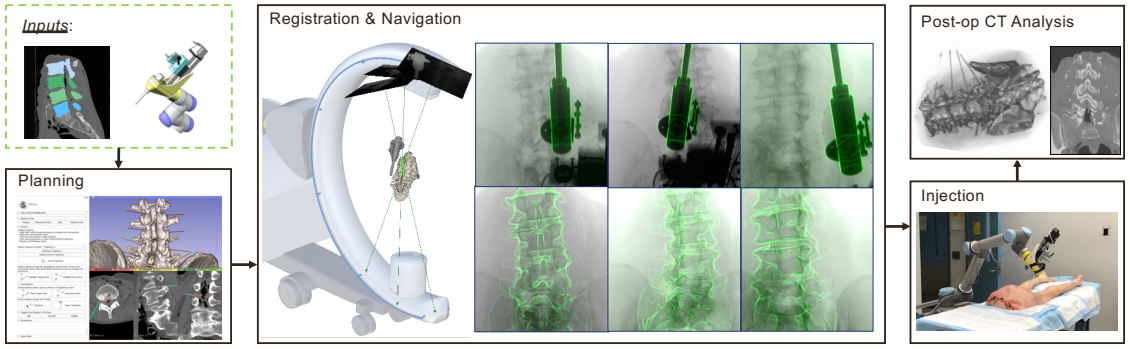
Spine Injection Navigation Pipeline



[15] **Gao, C.***, Phalen, H.*, Maraglit, A., Ma, J., Ku, P., Unberath, M., Taylor, R., Jain, A. and Armand, M. 2022 Fluoroscopy-Guided Robotic System for Transforaminal Lumbar Epidural Injections. Under Review of TMRB
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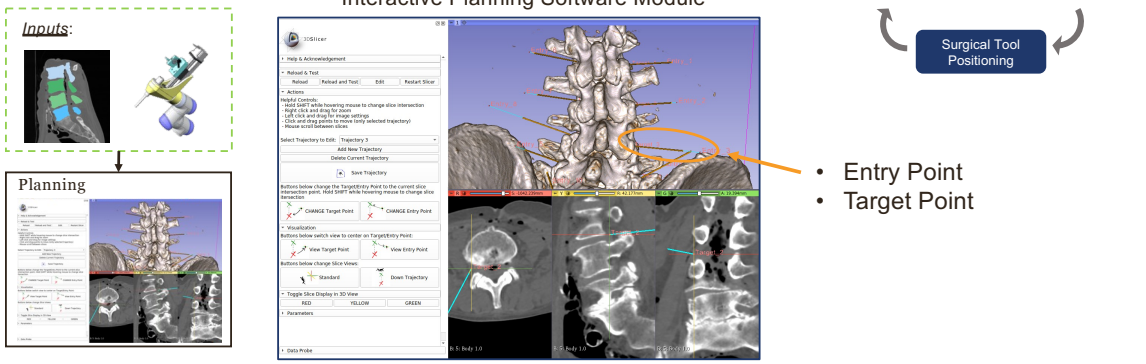
Overall Spine Injection Navigation Pipeline



Credit: Interactive Planning Module developed by Henry Phalen

[15] **Gao, C.***, Phalen, H.*, Maraglit, A., Ma, J., Ku, P., Unberath, M., Taylor, R., Jain, A. and Armand, M. 2022 Fluoroscopy-Guided Robotic System for Transforaminal Lumbar Epidural Injections. Under Review of TMRB
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Spine Injection Navigation Pipeline

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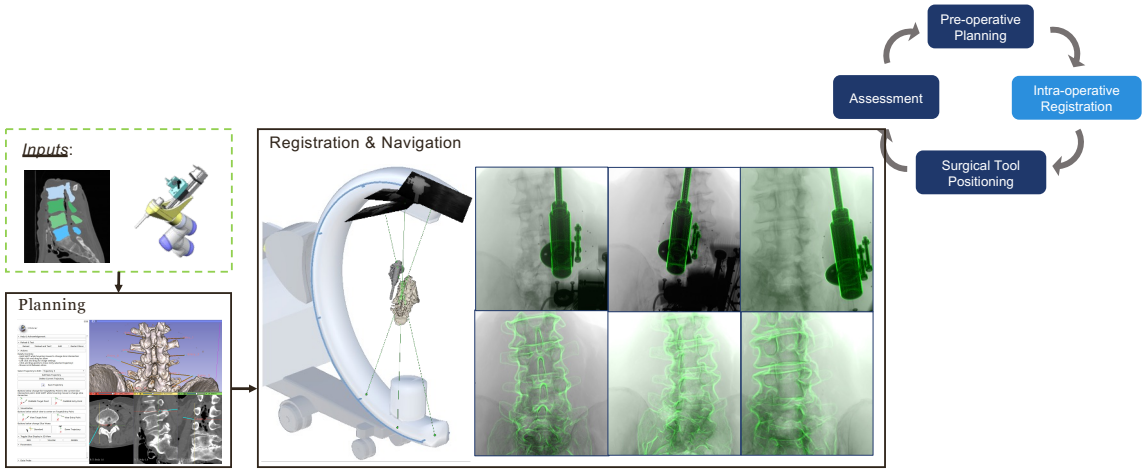

[15] **Gao, C.***, Phalen, H.*, Maraglit, A., Ma, J., Ku, P., Unberath, M., Taylor, R., Jain, A. and Armand, M. 2022 Fluoroscopy-Guided Robotic System for Transforaminal Lumbar Epidural Injections. Under Review of TMRB
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Registration Methods

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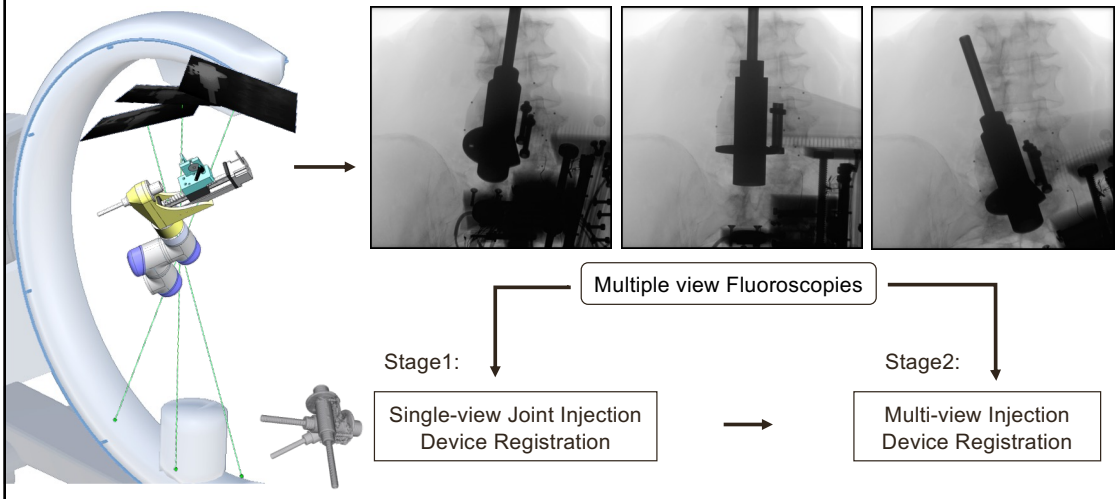
Injection Device Registration Pipeline



[15] **Gao, C.***, Phalen, H.*, Maraglit, A., Ma, J., Ku, P., Unberath, M., Taylor, R., Jain, A. and Armand, M. 2022 Fluoroscopy-Guided Robotic System for Transforaminal Lumbar Epidural Injections. Under Review of TMRB
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Registration Methods

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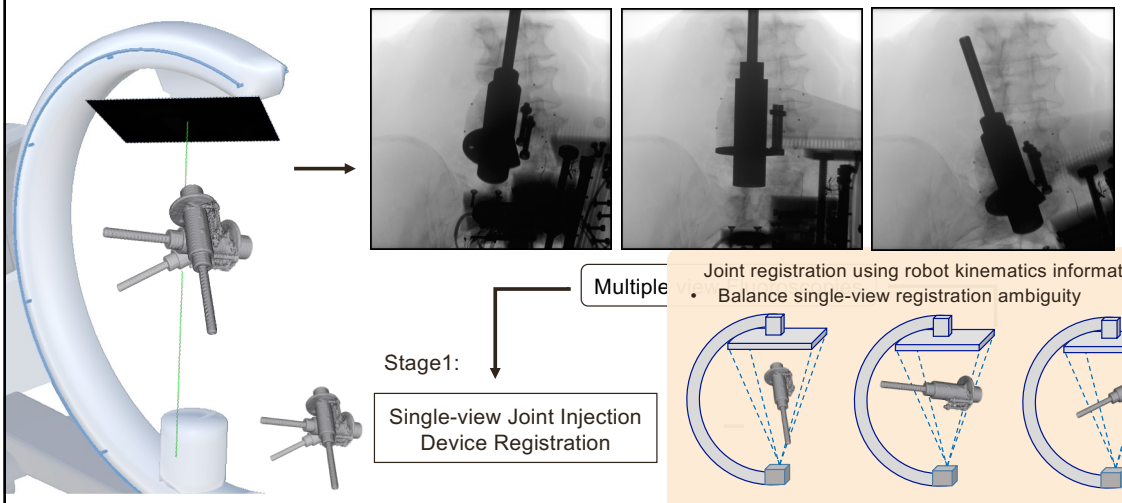
Joint Injection Device Registration



[15] **Gao, C.***, Phalen, H.*, Maraglit, A., Ma, J., Ku, P., Unberath, M., Taylor, R., Jain, A. and Armand, M. 2022 Fluoroscopy-Guided Robotic System for Transforaminal Lumbar Epidural Injections. Under Review of TMRB
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Registration Methods

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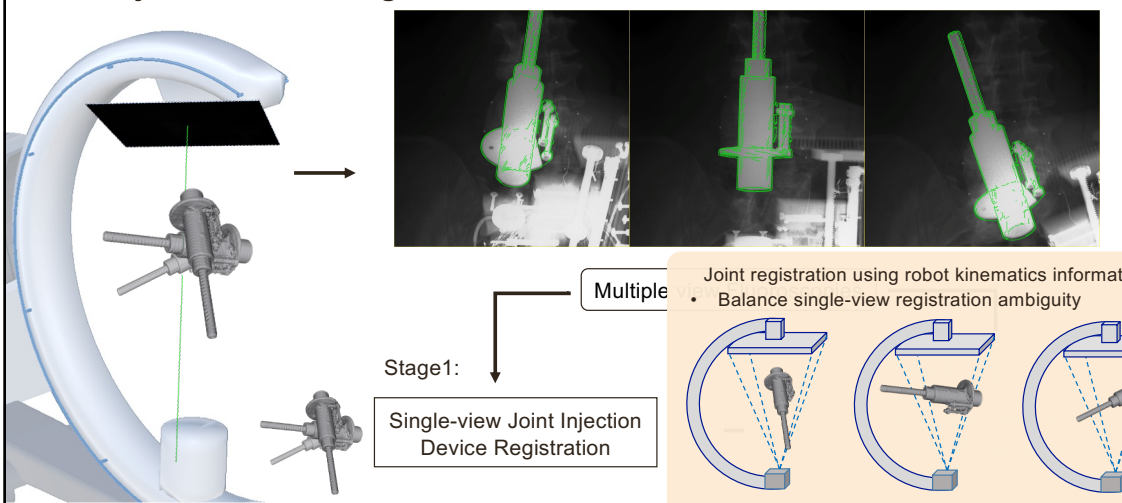
Joint Injection Device Registration



[15] **Gao, C.***, Phalen, H.*, Maraglit, A., Ma, J., Ku, P., Unberath, M., Taylor, R., Jain, A. and Armand, M. 2022 Fluoroscopy-Guided Robotic System for Transforaminal Lumbar Epidural Injections. Under Review of TMRB
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Simulation Study of Injection Device Registration

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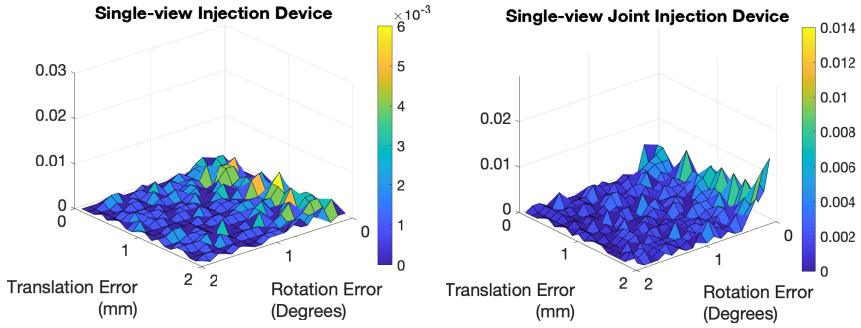
Simulated 1,000 Registrations with Randomized Geometries



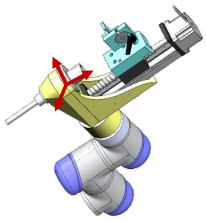


Table: Injection Device Registration Pose Errors

	Translation (mm)	Rotation (degree)
Single Object	2.15 ± 1.57	1.62 ± 1.40
Joint Registration	**1.73 ± 1.17**	**0.91 ± 0.92**

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Registration Pipeline

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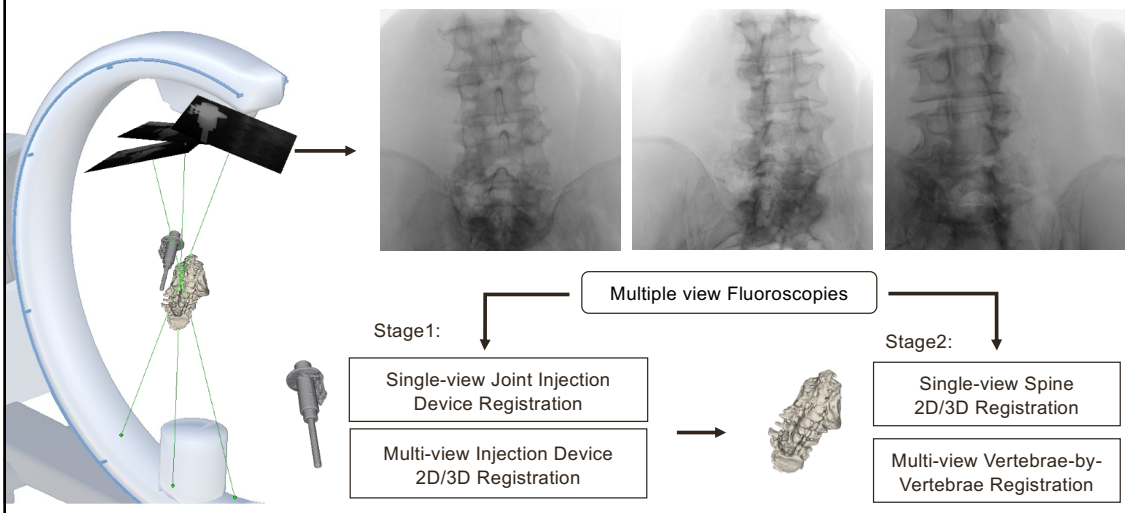

[15] **Gao, C.***, Phalen, H.*, Maraglit, A., Ma, J., Ku, P., Unberath, M., Taylor, R., Jain, A. and Armand, M. 2022 Fluoroscopy-Guided Robotic System for Transforaminal Lumbar Epidural Injections. Under Review of TMRB
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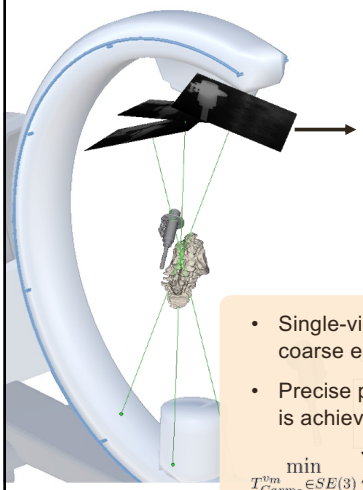
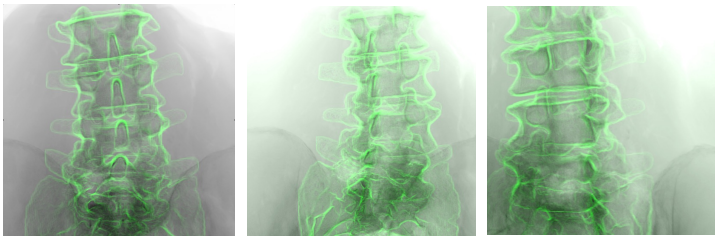
Registration Pipeline



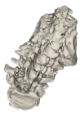


Multiple view Fluoroscopies

- Single-view rigid spine registration provides a coarse estimation
- Precise pose estimation of individual vertebra is achieved by multi-component optimization

$$\min_{T^{v_m}_{Carm_0} \in SE(3)} \sum_{k=1}^{K} \mathcal{S}\left(I_k^S, \mathcal{P}\left(\sum_{m=1}^{M} V_m; T^{v_m}_{Carm_0}, T^{Carm_k}_{Carm_0}\right)\right)$$

Loop every vertebra



Stage2:

Single-view Spine 2D/3D Registration

Multi-view Vertebrae-by-Vertebrae Registration

[15] **Gao, C.***, Phalen, H.*, Maraglit, A., Ma, J., Ku, P., Unberath, M., Taylor, R., Jain, A. and Armand, M. 2022 Fluoroscopy-Guided Robotic System for Transforaminal Lumbar Epidural Injections. Under Review of TMRB
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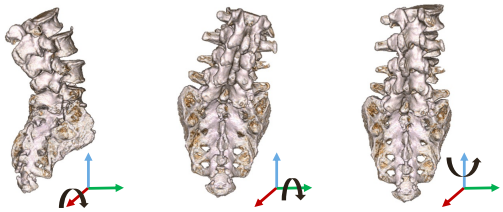
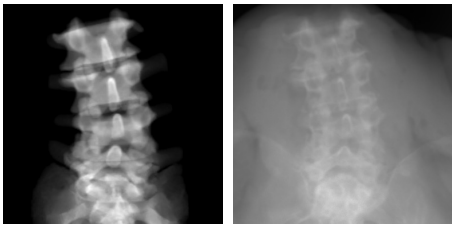
Spine Registration Simulation Study

Simulate Spine Deformation using CT Segmentations

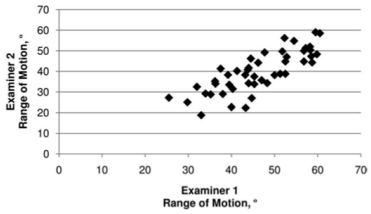


3D Rendering of Simulated Spine Deformations
Rotation sampled uniformly from [-12.5, 12.5] degrees



Synthetic X-ray of Spine Segmentation and CT

Spine Range of Motion[16]



40 - 60 degrees for normal adult

[16] Johnson, K.D., Kim, K.M., Yu, B.K., Saliba, S.A. and Grindstaff, T.L., 2012. Reliability of thoracic spine rotation range-of-motion measurements in healthy adults. Journal of athletic training, 47(1), pp.52-60.

Spine Registration Simulation Study

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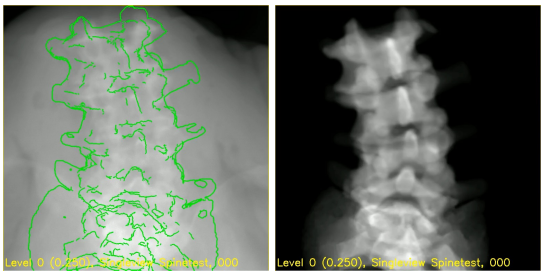
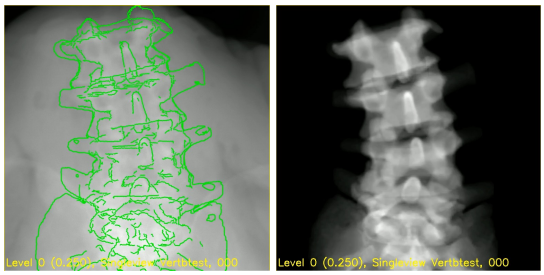
Single-view C-arm Geometry

Rigid Spine Registration



Vertebrae-by-Vertebrae Registration



[15] **Gao, C.***, Phalen, H.*, Maraglit, A., Ma, J., Ku, P., Unberath, M., Taylor, R., Jain, A. and Armand, M. 2022 Fluoroscopy-Guided Robotic System for Transforaminal Lumbar Epidural Injections. Under Review of TMRB
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Spine Registration Simulation Study

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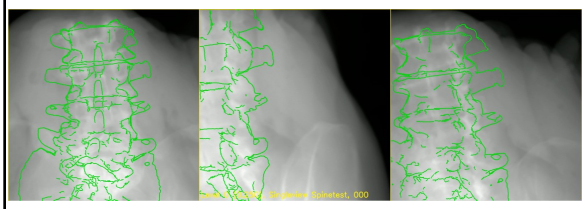
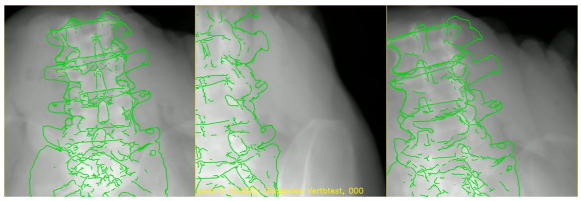
Multi-view C-arm Geometry

Rigid Spine Registration



Vertebrae-by-Vertebrae Registration



[15] **Gao, C.***, Phalen, H.*, Maraglit, A., Ma, J., Ku, P., Unberath, M., Taylor, R., Jain, A. and Armand, M. 2022 Fluoroscopy-Guided Robotic System for Transforaminal Lumbar Epidural Injections. Under Review of TMRB
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Spine Registration Simulation Study

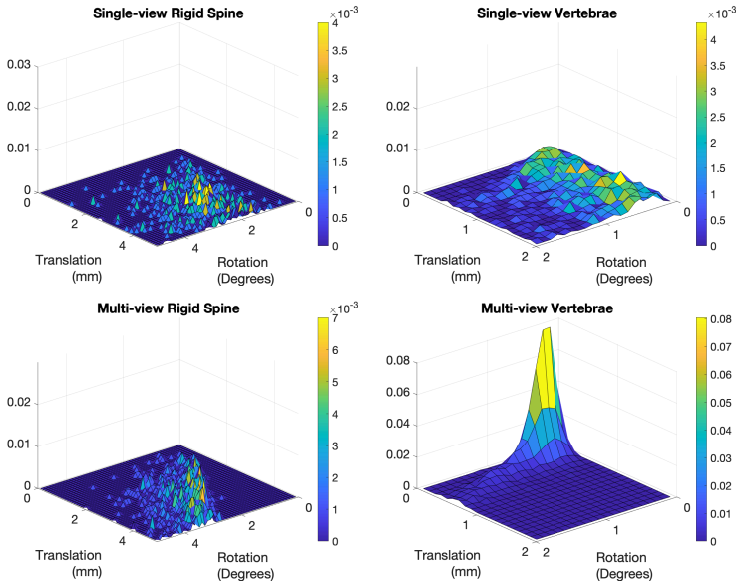
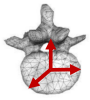


Table: Numeric Registration Pose Error

		Translation (mm)	Rotation (degrees)
Single-view	Rigid Spine	4.79±2.36	2.79±1.70
	Vertb-by-Vertb	3.50±2.91	1.05±1.88
Multi-view	Rigid Spine	3.69±1.60	2.89±1.23
	Vertb-by-Vertb	**0.76±0.28**	**0.88±0.68**



[15] **Gao, C.***, Phalen, H.*, Maraglit, A., Ma, J., Ku, P., Unberath, M., Taylor, R., Jain, A. and Armand, M. 2022 Fluoroscopy-Guided Robotic System for Transforaminal Lumbar Epidural Injections. Under Review of TMRB
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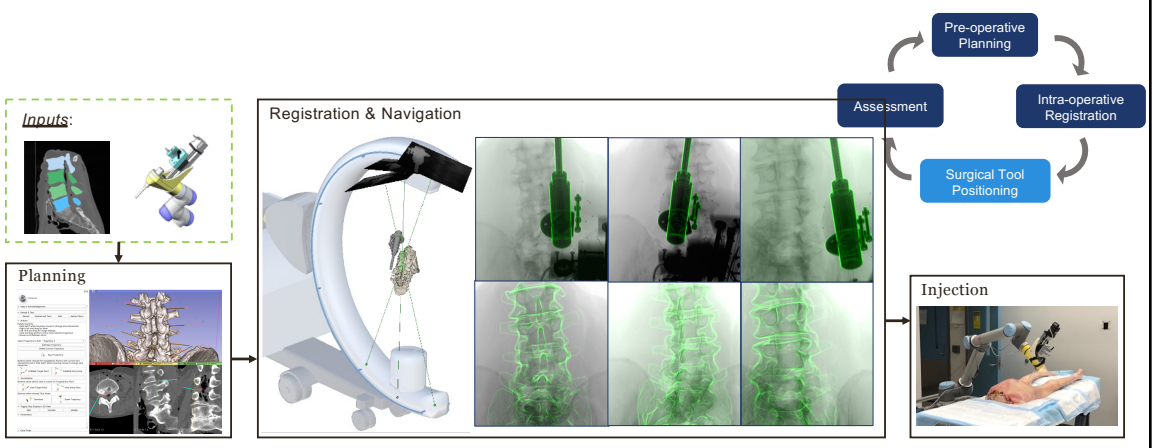
Overall Spine Injection Navigation Pipeline



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System Setup

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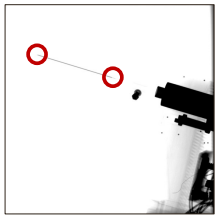
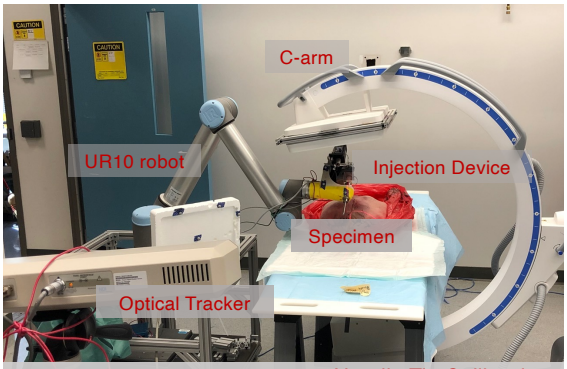
Hand-eye Calibration

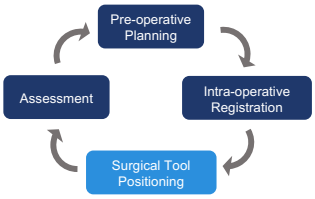
- Introduced before

Needle Tip Calibration



- Triangulate the needle tip point in the injection model frame using 6-7 X-ray images





Credit: The Syringe mount is designed by Justin Ma

[15] **Gao, C.***, Phalen, H.*, Maraglit, A., Ma, J., Ku, P., Unberath, M., Taylor, R., Jain, A. and Armand, M. 2022 Fluoroscopy-Guided Robotic System for Transforaminal Lumbar Epidural Injections. Under Review of TMRB
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Robotic Spine Needle Injection Cadaver Study

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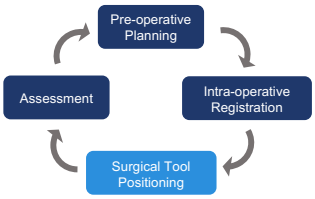
Performed 10 Robotic Needle Injections



Robot Injection Experiment Video

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Robotic Spine Needle Injection Cadaver Study

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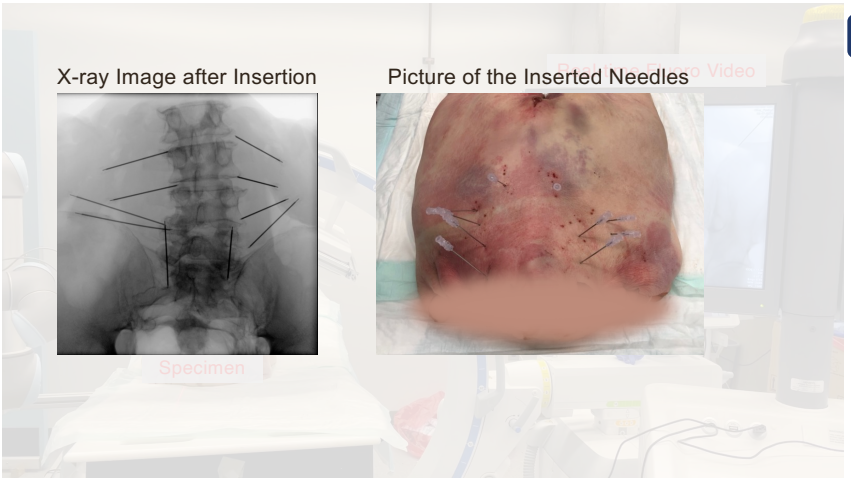
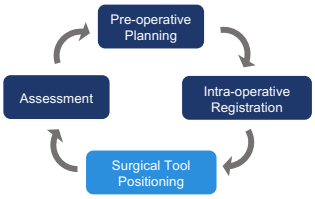
Performed 10 Robotic Needle Injections





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Experienced Clinician Manual Injection

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Performed 10 Needle Injections using the same Plannings

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Spine Injection Results

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Post-op Analysis

- Took post-op CT scans with inserted needles
- 3D/3D Registration between pre-op and post-op CT of each individual vertebra
- Annotated target/entry points for comparison

Table: Cadaveric Needle Injection Accuracy

ID	Needle Tip Error (mm)		Orientation Error (degrees)	
	Robot	Surgeon	Robot	Surgeon
1	3.13	9.46	5.13	5.77
2	6.13	11.35	1.85	8.30
3	7.02	6.17	2.40	13.20
4	7.14	12.29	4.60	6.98
5	4.36	6.88	2.06	9.28
6	1.54	8.46	1.56	8.61
7	5.14	3.36	2.63	7.05
8	8.01	7.02	5.52	20.88
9	1.57	5.28	2.95	13.46
10	6.85	5.56	7.37	5.51
Mean	5.09 ± 2.36	7.58 ± 2.80	3.61 ± 1.93	9.90 ± 4.73

[15] **Gao, C.***, Phalen, H.*, Maraglit, A., Ma, J., Ku, P., Unberath, M., Taylor, R., Jain, A. and Armand, M. 2022 Fluoroscopy-Guided Robotic System for Transforaminal Lumbar Epidural Injections. Under Review of TMRB
* indicates joint first co-authors

Clinical Evaluation

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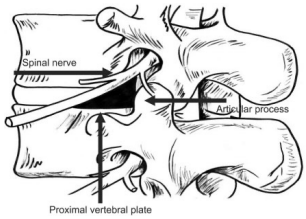
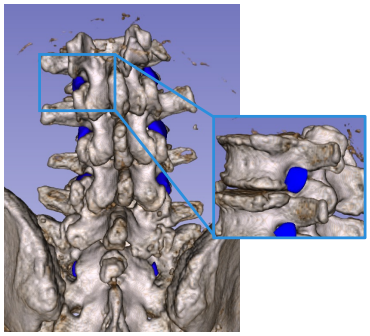
Triangle Safety Zone

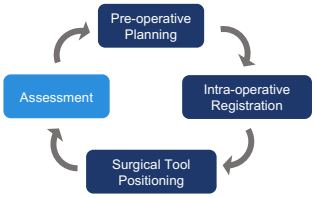
- Injections through the safety triangle allow the steroid to be injected more effectively and safely
- All of our injections were within the triangle safety zones



Definition



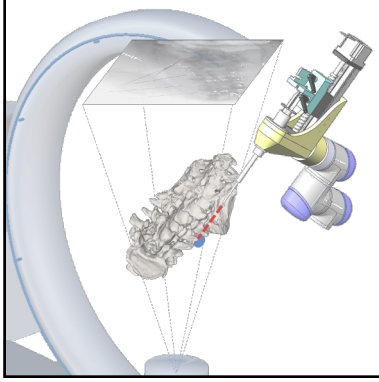
Our annotations



[15] **Gao, C.***, Phalen, H.*, Maraglit, A., Ma, J., Ku, P., Unberath, M., Taylor, R., Jain, A. and Armand, M. 2022 Fluoroscopy-Guided Robotic System for Transforaminal Lumbar Epidural Injections. Under Review of TMRB
* indicates joint first co-authors

Conclusion and Contributions

- An autonomous fluoroscopy-guided robotic spine needle injection system
- Present the superiority of multi-view, multi-component 2D/3D registration over single-view, single object 2D/3D registration with simulation experiments
- Present the improved performance using our robotic injections compared to clinician's manual injections in controlled cadaver experiments



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Acknowledgment

Mr. Henry Phalen: Developed the interactive needle planning module, the robot closed-loop control module, contributed to system calibration and trouble shooting, jointly worked on both phantom and cadaver experiments, and post-op analysis

Mr. Adam Margalit: Built the spine testing phantom (not presented here), provided clinical guidance, coordination and equipment support, jointly worked on both phantom and cadaver experiments

Mr. Justin Ma: Developed the robot closed-loop control module

Mr. Ping-Cheng Ku: Helped annotate the triangle safety zone for post-op analysis

Dr. Akhil Chhatre and Dr. David Cohen: Performed manual needle injections

Related Publications/Manuscripts:

- **Gao, C.***, Phalen, H.*, Maraglit, A., Ma, J., Ku, P., Unberath, M., Taylor, R., Jain, A. and Armand, M. 2022 Fluoroscopy-Guided Robotic System for Transforaminal Lumbar Epidural Injections. Under Review of TMRB
- Margalit, A., Phalen, H., **Gao, C.**, Ma, J., Suresh, K.V., Jain, P., Farvardin, A., Taylor, R.H., Armand, M., Chattre, A. and Jain, A., 2022. Autonomous Spinal Robotic System for Transforaminal Lumbar Epidural Injections: A Proof of Concept of Study. Global Spine Journal, p.21925682221096625.

* indicates joint first co-authors

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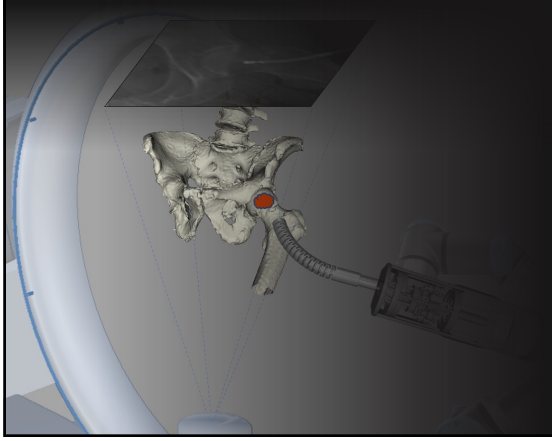
Part I – Clinical Application Developments

Core Decompression of the Hip



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Core Decompression of the Hip

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Osteonecrosis

- A disease that results from loss of blood supply to the bone
- Usually progresses to femoral head collapse, and eventually total hip arthroplasty
- **Core Decompression** -- Reduce the pressure in the femoral head with osteonecrosis

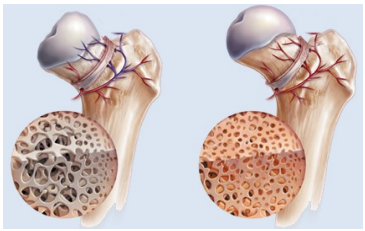
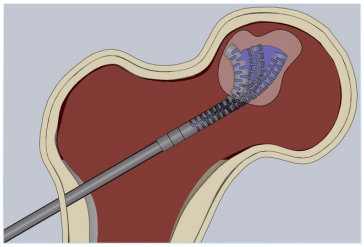


Illustration of Osteonecrosis[17]

Less-invasive Surgical Procedure

- Access the lesion through the narrow femoral neck by drilling
- Remove and grafting the lesion



Concept of Curvature Drilling

[17] https://www.spineorthocenter.com/services/orthopedic/joint-diseases/osteonecrosis/

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Continuum Manipulator

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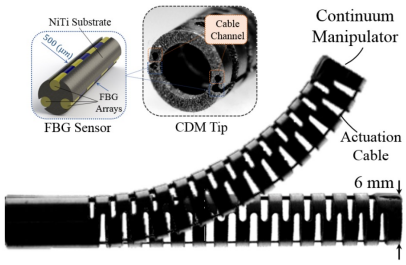
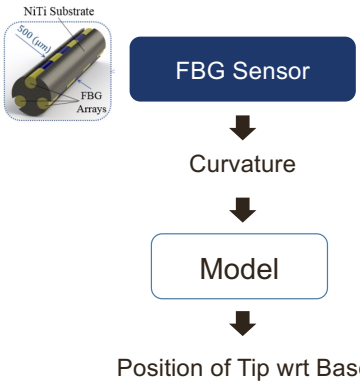
Custom-designed Continuum Manipulator
with embedded Shape Sensing

- Accurate intraoperative pose and shape feedback during bone drilling is challenging



Continuum manipulator and FBG [18]



[18] Sefati, S., Hegeman, R., Alambeigi, F., Iordachita, I., & Armand, M. (2019, April). FBG-based position estimation of highly deformable continuum manipulators: Model-dependent vs. data-driven approaches. In 2019 International Symposium on Medical Robotics (ISMR) (pp. 1-6). IEEE

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Continuum Manipulator

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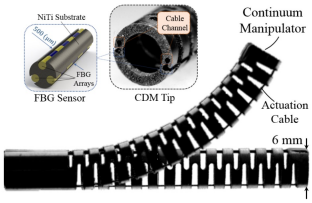
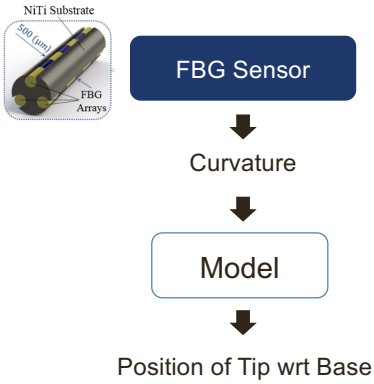
Challenges of FBG Shape Sensing

- Fiber Bragg Grating (FBG) sensing doesn't have enough sensing points, which might not be accurate
- Large errors when touching obstacles[19]
- Internal sensing does not close the registration loop with respect to the bone





[19] Sefati, S., Hegeman, R., Alambeigi, F., Iordachita, I., & Armand, M. (2019, April). FBG-based position estimation of highly deformable continuum manipulators: Model-dependent vs. data-driven approaches. In 2019 International Symposium on Medical Robotics (ISMR) (pp. 1-6). IEEE

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Previous Efforts

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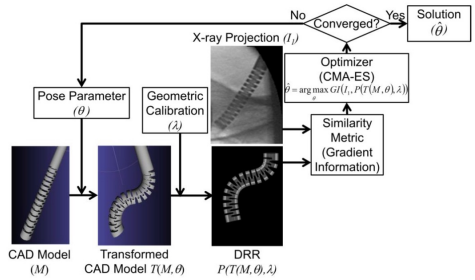
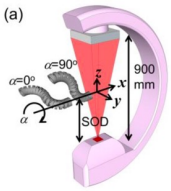
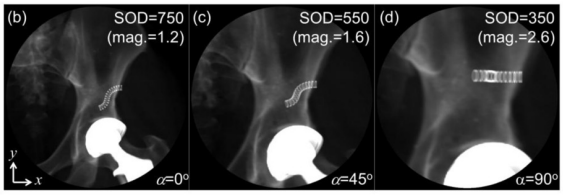
Limitations of Otake et al.'s work

- Manual initialization
- Only tested in simulation. The simulation was not yet realistic
- Not integrated/tested with the robot system







[21] Otake, Y., Murphy, R.J., Kutzer, M.D., Taylor, R.H. and Armand, M., 2014, March. Piecewise-rigid 2D-3D registration for pose estimation of snake-like manipulator using an intraoperative x-ray projection. In Medical Imaging 2014: Image-Guided Procedures, Robotic Interventions, and Modeling (Vol. 9036, pp. 185-190). SPIE.

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Motivation

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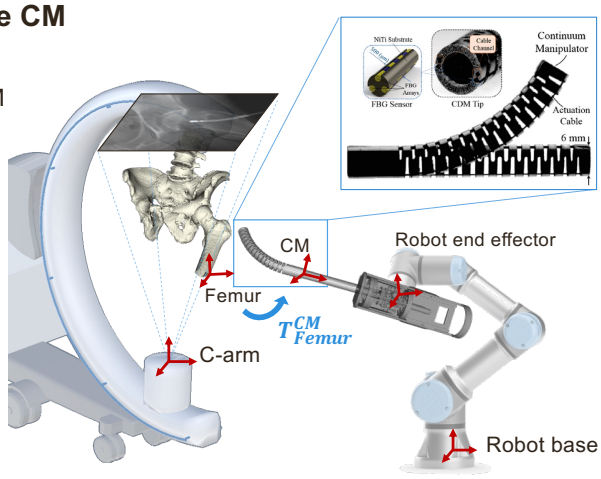
X-ray Image-based navigation of the CM

- **Rigid** Pose estimation of femur and the CM
- **Flexible** CM Shape estimation
- Robot relative to the bone anatomy, T_{Femur}^{CM}



CM Navigation Concept[20]

[20] **Gao, C.,** Phalen, H., Sefati, S., Ma, J., Taylor, R.H., Unberath, M. and Armand, M., 2021. Fluoroscopic navigation for a surgical robotic system including a continuum manipulator. IEEE Transactions on Biomedical Engineering, 69(1), pp.453-464.

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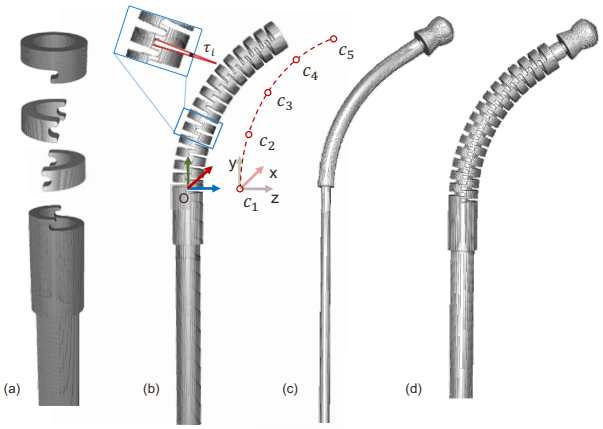
CM Model and X-ray Simulation

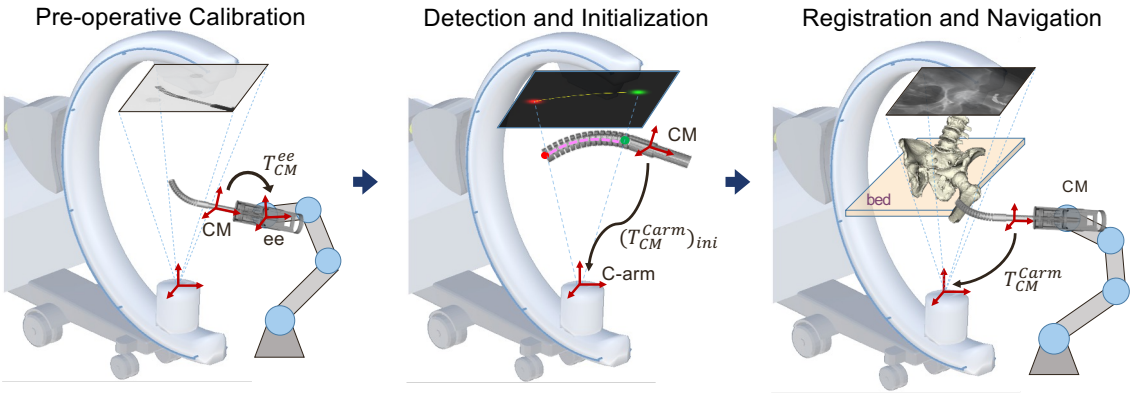


CM 3D Model

Example X-ray Simulation

[20] **Gao, C.,** Phalen, H., Sefati, S., Ma, J., Taylor, R.H., Unberath, M. and Armand, M., 2021. Fluoroscopic navigation for a surgical robotic system including a continuum manipulator. IEEE Transactions on Biomedical Engineering, 69(1), pp.453-464.

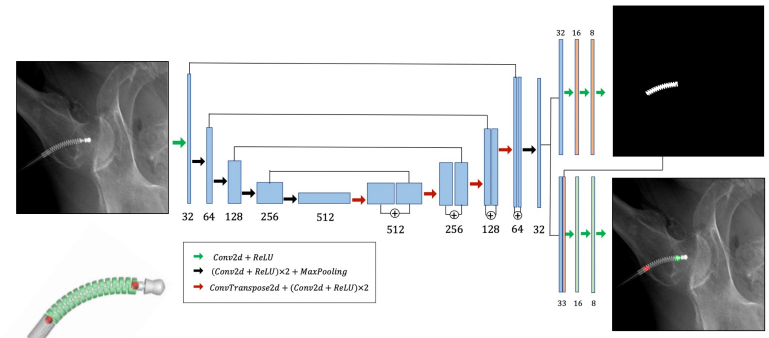
CM Navigation Pipeline

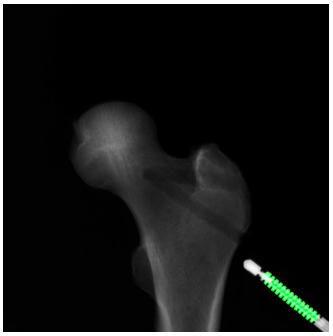


[20] **Gao, C.,** Phalen, H., Sefati, S., Ma, J., Taylor, R.H., Unberath, M. and Armand, M., 2021. Fluoroscopic navigation for a surgical robotic system including a continuum manipulator. IEEE Transactions on Biomedical Engineering, 69(1), pp.453-464.

Learning-based CM Detection

Concurrent segmentation and landmark detection[21]





Example real X-ray detection results

Table: CM Detection Accuracy

	Landmark Error (mm)	Segmentation DICE Score
Simulation	0.449 ± 0.525	0.993 ± 0.002
Real X-ray	2.62 ± 1.05	0.920 ± 0.068

[21] **C. Gao*,** M. Unberath*, R. Taylor, & M. Armand (2019). Localizing dexterous surgical tools in X-ray for image-based navigation. IPCAI 2019 Long Abstract

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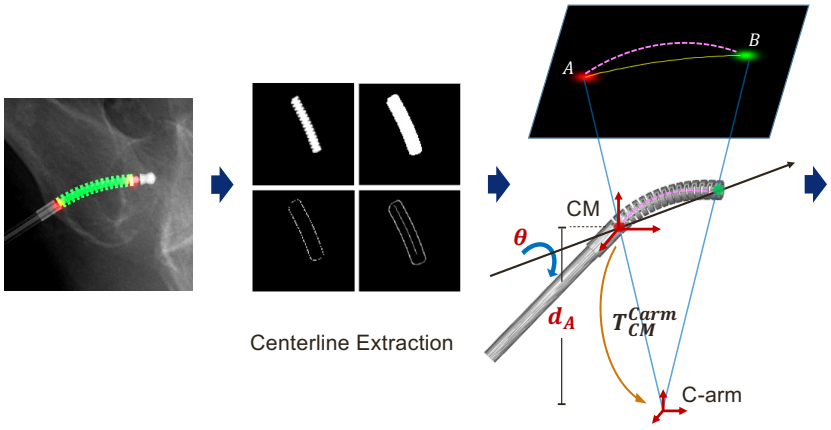
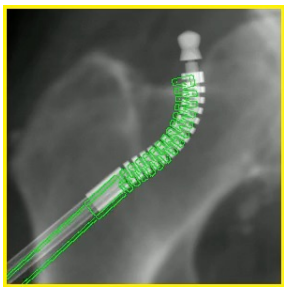
Single-view CM Registration

- Automatic initialization of CM registration
- The landmarks regularize the registration search space (reprojection penalty)



Centerline Extraction



Example Registration Movie (Single-view)

[20] **Gao, C.,** Phalen, H., Sefati, S., Ma, J., Taylor, R.H., Unberath, M. and Armand, M., 2021. Fluoroscopic navigation for a surgical robotic system including a continuum manipulator. IEEE Transactions on Biomedical Engineering, 69(1), pp.453-464.

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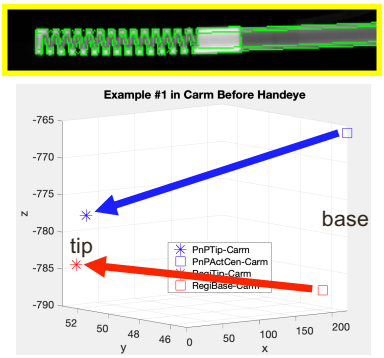
CM Registration

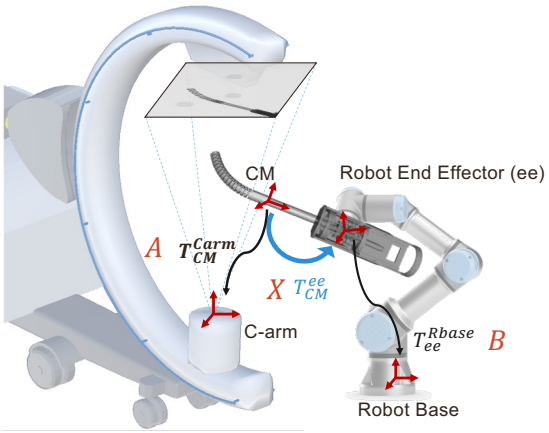
Severe Registration Ambiguity

- Single-view registration by itself has ambiguity
- The CM is small, symmetric and flexible



Affects the hand-eye calibration accuracy

- Solve an axyb problem



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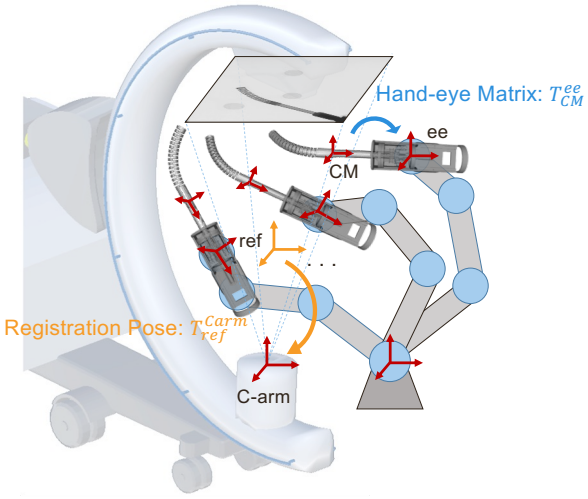
Joint CM Registration

Our Solution to Balance Registration Ambiguity

- Use robot kinematics to jointly register multiple CM configurations together
- A modified, image-based hand-eye calibration method

$$\min_{T_{ref}^{Carm},T_{CM}^{ee}\in SE(3),\tau_i} \sum_{m=1}^{M} \mathcal{S}\Big(I_k, \mathcal{P}(\sum_{j=1}^{J} V_j; T_{ref}^{Carm}, T_{CM}^{ee}, \tau_i)\Big)$$



Joint CM Registration

[20] **Gao, C.,** Phalen, H., Sefati, S., Ma, J., Taylor, R.H., Unberath, M. and Armand, M., 2021. Fluoroscopic navigation for a surgical robotic system including a continuum manipulator. IEEE Transactions on Biomedical Engineering, 69(1), pp.453-464.

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CM Registration Simulation Study

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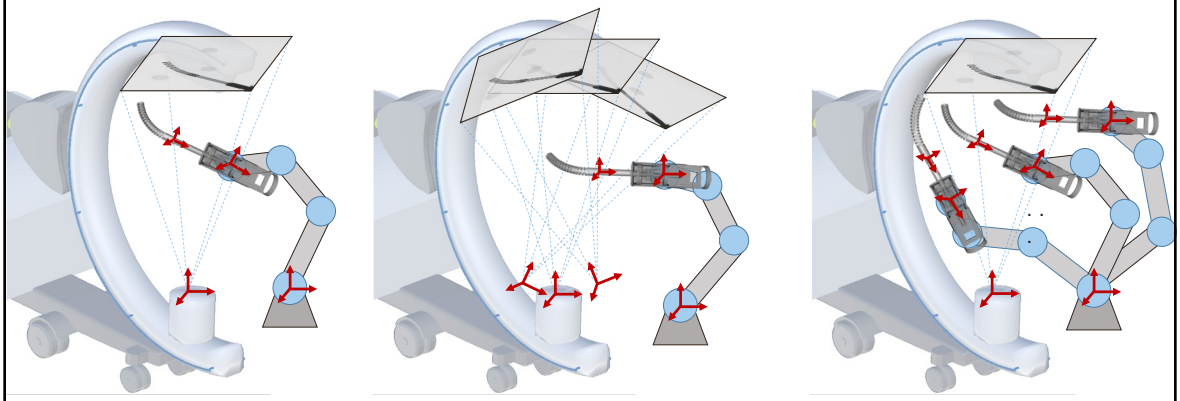
Single-view Registration | **Multi-view Registration** | **Joint CM Registration**



[20] **Gao, C.,** Phalen, H., Sefati, S., Ma, J., Taylor, R.H., Unberath, M. and Armand, M., 2021. Fluoroscopic navigation for a surgical robotic system including a continuum manipulator. IEEE Transactions on Biomedical Engineering, 69(1), pp.453-464.

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CM Registration Simulation Study

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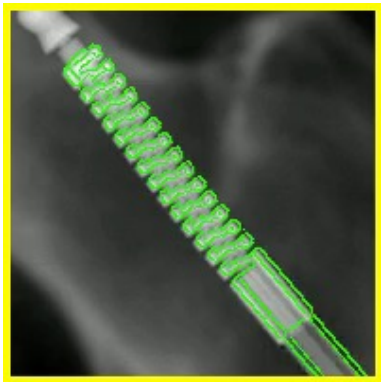
Single-view Registration

Simulated X-ray Image



Registration Movie

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CM Registration Simulation Study

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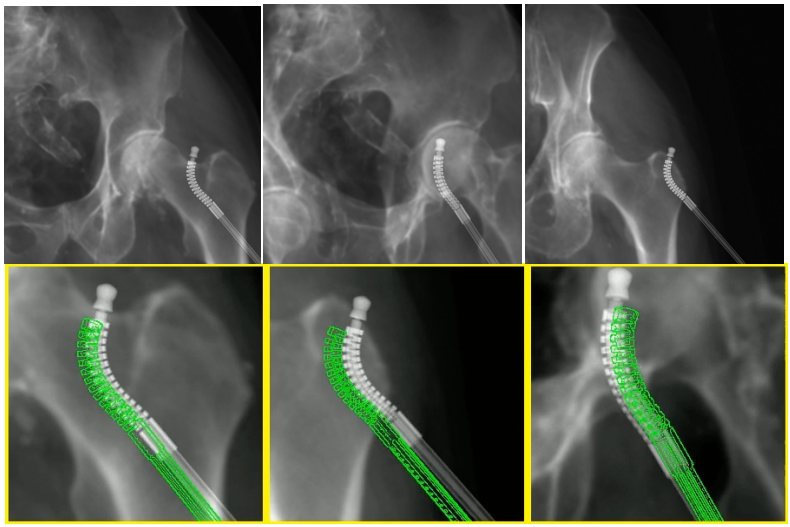
Multi-view Registration



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CM Registration Simulation Study

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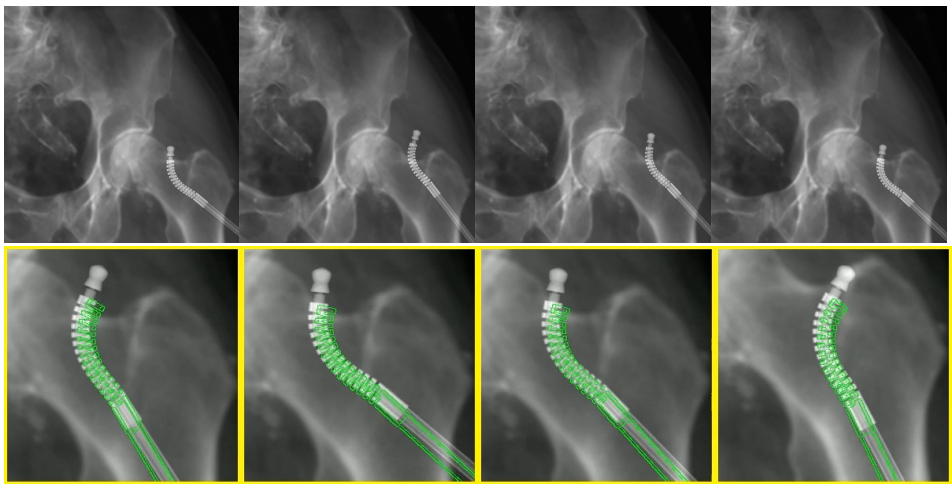
Joint CM Registration



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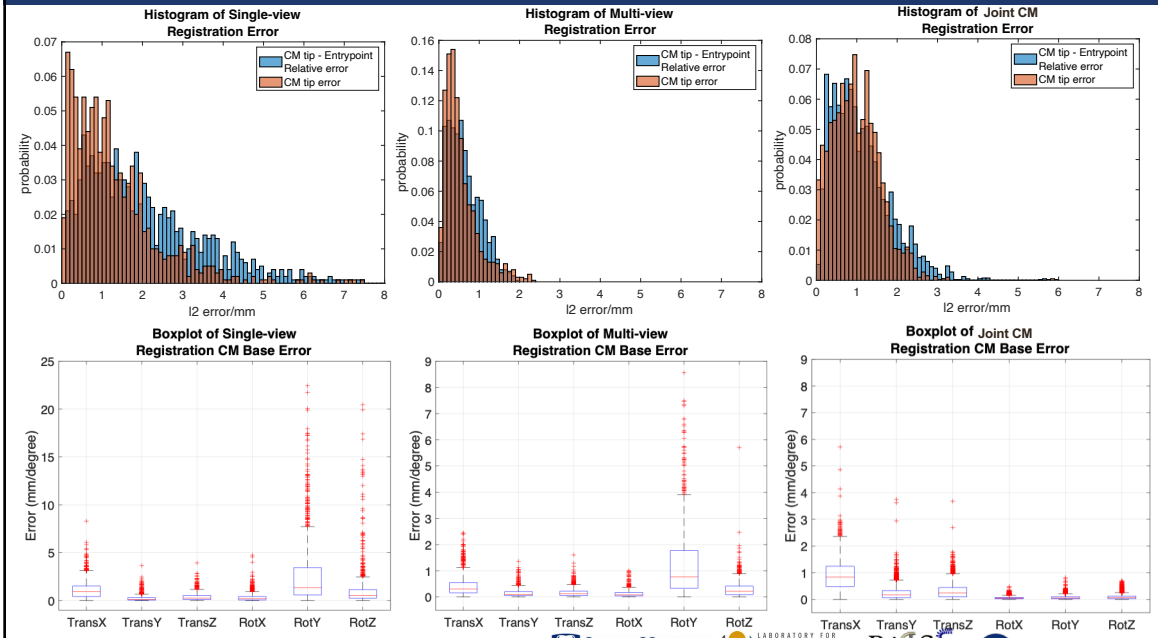
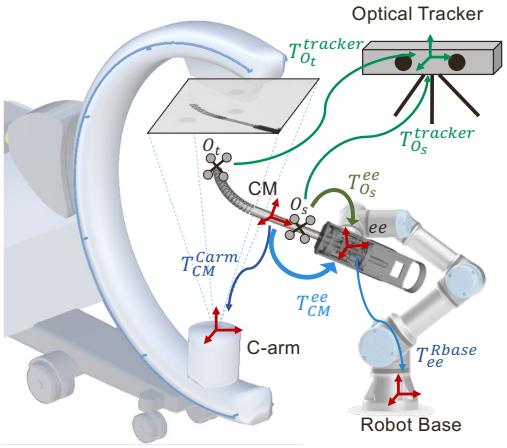
Simulation Study Results

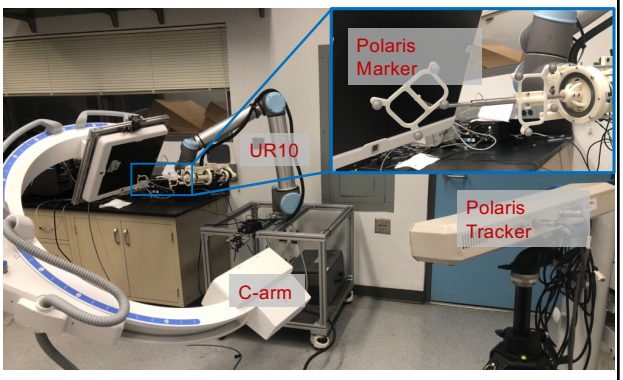


System Calibration

CM Hand-eye Calibration



Mean Tip Difference: 2.15 ± 0.50 mm



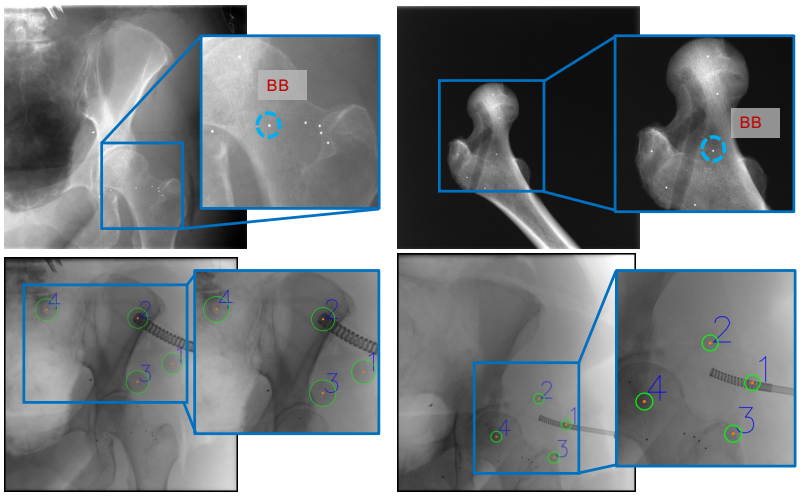
[20] **Gao, C.,** Phalen, H., Sefati, S., Ma, J., Taylor, R.H., Unberath, M. and Armand, M., 2021. Fluoroscopic navigation for a surgical robotic system including a continuum manipulator. IEEE Transactions on Biomedical Engineering, 69(1), pp.453-464.

Core Decompression Cadaveric Experiment

[20] **Gao, C.,** Phalen, H., Sefati, S., Ma, J., Taylor, R.H., Unberath, M. and Armand, M., 2021. Fluoroscopic navigation for a surgical robotic system including a continuum manipulator. IEEE Transactions on Biomedical Engineering, 69(1), pp.453-464.

Core Decompression Cadaveric Experiment

Ground truth poses were obtained by solving a PnP problem using BB and fiducial landmarks



[20] **Gao, C.,** Phalen, H., Sefati, S., Ma, J., Taylor, R.H., Unberath, M. and Armand, M., 2021. Fluoroscopic navigation for a surgical robotic system including a continuum manipulator. IEEE Transactions on Biomedical Engineering, 69(1), pp.453-464.

CM Cadaveric Experiment

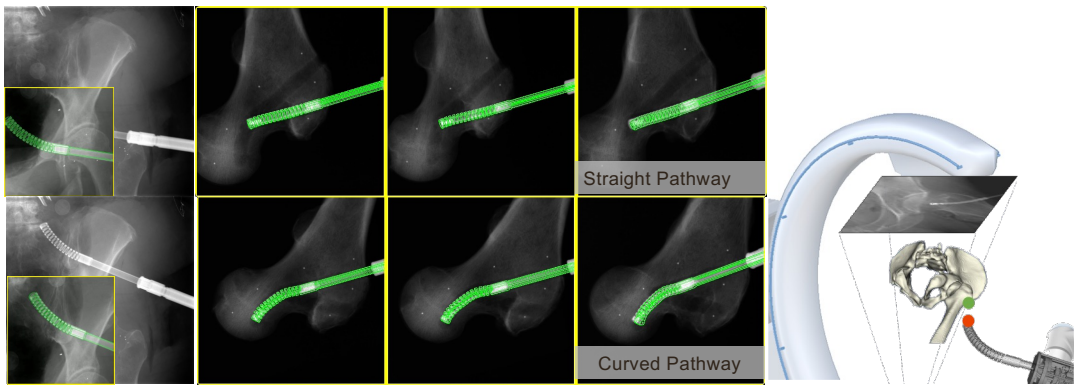


Table: CM Tip & Femur Entry Point Error[12]

Trial ID	I	II	III	IV	V
CM Tip Position (mm)	2.73	2.44	2.77	4.20	2.09
Femur Entry Point (mm)	1.21	2.23	1.91	2.35	2.04
Relative (mm)	2.95	3.31	3.65	4.10	1.83

Femur entry point relative to CM tip
Mean Error: $\mathbf{2.86 \pm 0.80\ mm}$

[20] **Gao, C.,** Phalen, H., Sefati, S., Ma, J., Taylor, R.H., Unberath, M. and Armand, M., 2021. Fluoroscopic navigation for a surgical robotic system including a continuum manipulator. IEEE Transactions on Biomedical Engineering, 69(1), pp.453-464.

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Conclusion and Contributions

Automatic Registration Pipeline

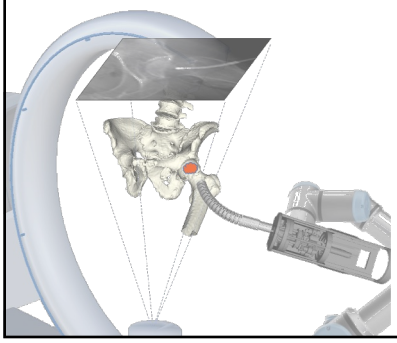
- A learning-based continuum manipulator detection method in X-ray images

Balanced Registration Ambiguity

- Jointly register multiple CM together and a modified hand-eye calibration method

System Validation

- Verified the the feasibility of applying purely fluoroscopic image-based registration for the CM navigation in simulation and cadaver experiments



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Acknowledgment

Mr. Henry Phalen: Contributed to registration algorithm design, helped with the continuum manipulator calibration and cadaver experiments

Dr. Shahriar Sefati: Developed the continuum manipulator optical marker-based hand-eye calibration and control modules, helped with the system testing and algorithm design

Mr. Justin Ma: Developed the improved version of continuum manipulator

Related Publications/Manuscripts:

- **Gao, C.**, Phalen, H., Sefati, S., Ma, J., Taylor, R.H., Unberath, M. and Armand, M., 2021. Fluoroscopic navigation for a surgical robotic system including a continuum manipulator. IEEE Transactions on Biomedical Engineering, 69(1), pp.453-464. **Selected as a Featured Article**
- **C. Gao***, M. Unberath*, R. Taylor, & M. Armand (2019). Localizing dexterous surgical tools in X-ray for image-based navigation. IPCAI 2019 Long Abstract

* indicates joint first co-authors

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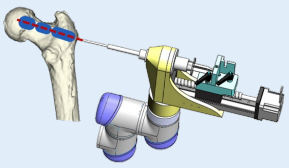
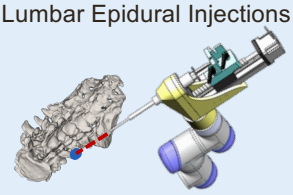
Introduction: Outline

Part I: Clinical Application Development

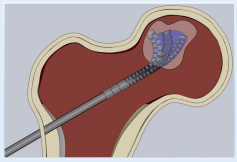
Femoroplasty



Lumbar Epidural Injections

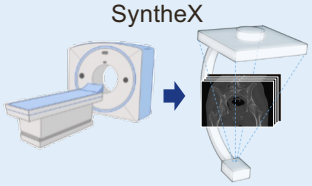


Core Decompression

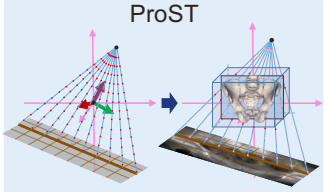


Part II: Machine Learning Investigations

SyntheX



ProST



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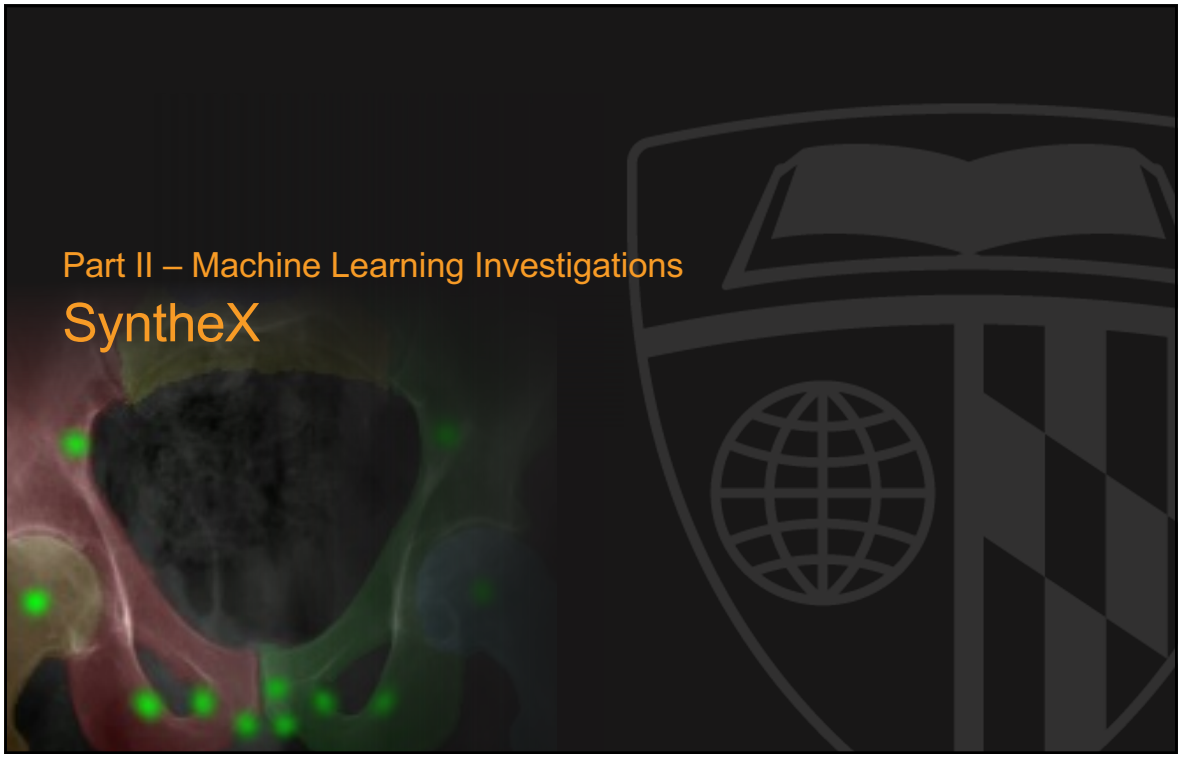

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Recap

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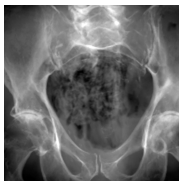
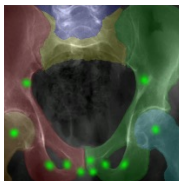
Machine Learning X-ray Detection Tasks

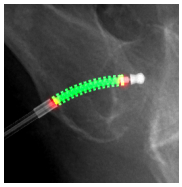
- Automatic Registration Initialization



Pelvic Detection Network



CM Detection Network



How do we generate training data?

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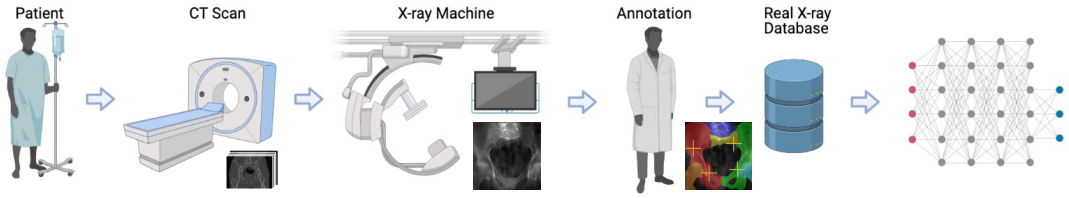
Motivation



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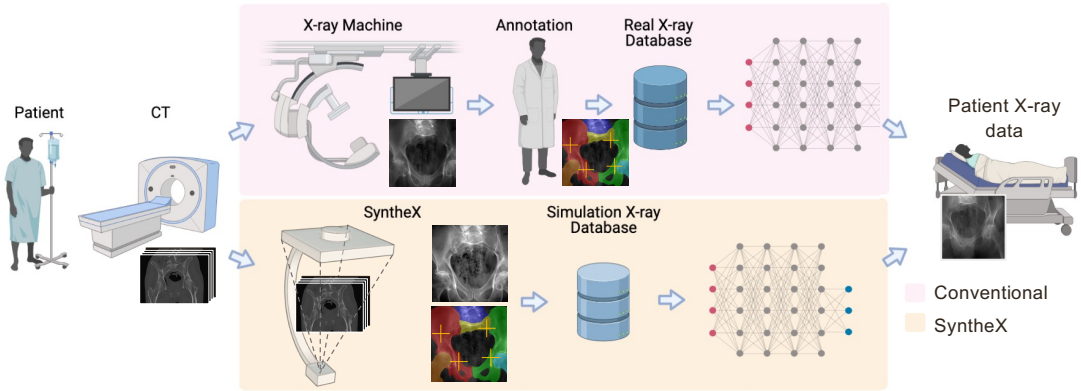
SyntheX

SyntheX: Realistic Synthesis for X-ray Image Analysis



[21] **Gao, C.,** Killeen, B.D., Hu, Y., Grupp, R.B., Taylor, R.H., Armand, M. and Unberath, M., 2022. SyntheX: Scaling Up Learning-based X-ray Image Analysis Through In Silico Experiments. Under Review of Nature Machine Intelligence

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Unique Cadaveric Pelvic X-ray Dataset

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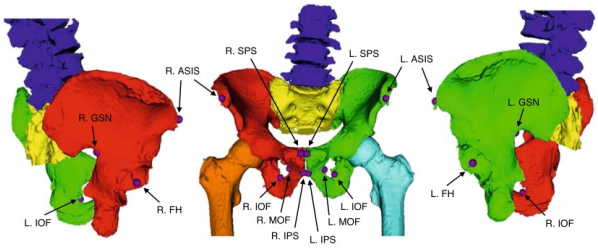
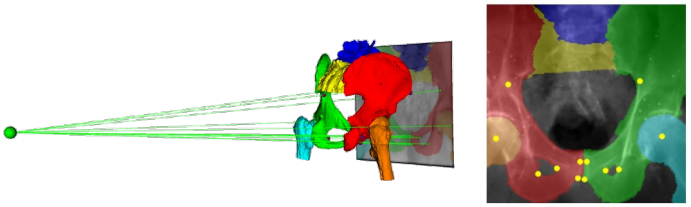
A cadaveric hip dataset[22]

- 6 cadaveric specimens
- 366 X-ray images
- All have registered "ground truth" pose of corresponding CT scans



14 anatomical landmarks & 6 pelvic segmentations



Credit: Dr. Robert Grupp published this valuable dataset

[22] Grupp, R. B., Unberath, M., Gao, C., Hegeman, R. A., Murphy, R. J., Alexander, C. P., ... & Taylor, R. H. (2020). Automatic annotation of hip anatomy in fluoroscopy for robust and efficient 2D/3D registration. *International journal of computer assisted radiology and surgery*, *15*(5), 759-769.

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Precisely Matched Simulation-Real Database

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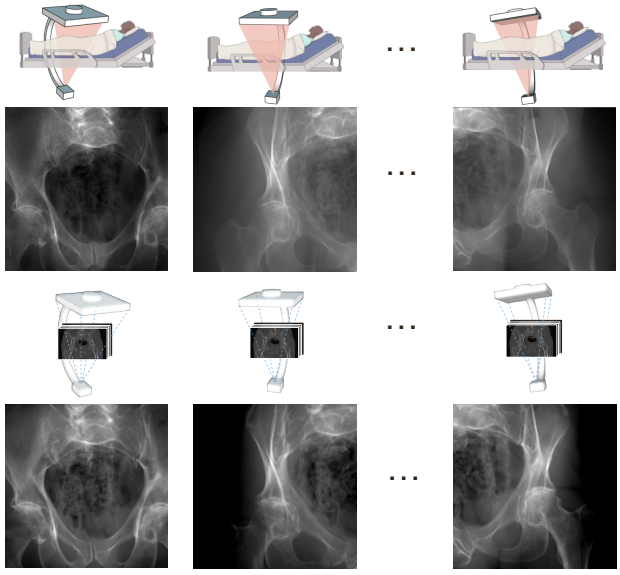
Real X-ray Database

Simulation X-ray Database



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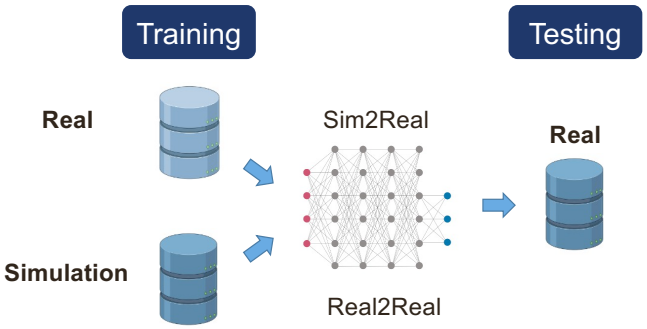
Precisely Controlled Sim2Real Benchmark Experiments



Sim2Real Techniques

- Domain Randomization
- Domain Adaptation
  - CycleGAN
  - Adversarial Discriminative Domain Adaptation

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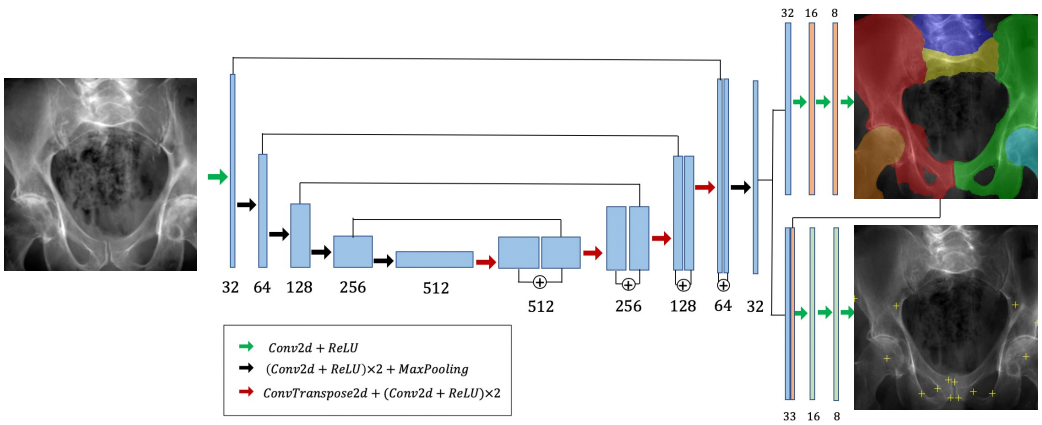
Concurrent Segmentation and Landmark Detection

Hip Imaging Downstream Task



[10] Grupp, R.B., Unberath, M., **Gao, C.**, Hegeman, R.A., Murphy, R.J., Alexander, C.P., Otake, Y., McArthur, B.A., Armand, M. and Taylor, R.H., 2020. Automatic annotation of hip anatomy in fluoroscopy for robust and efficient 2D/3D registration. International journal of computer assisted radiology and surgery, 15(5), pp.759-769.

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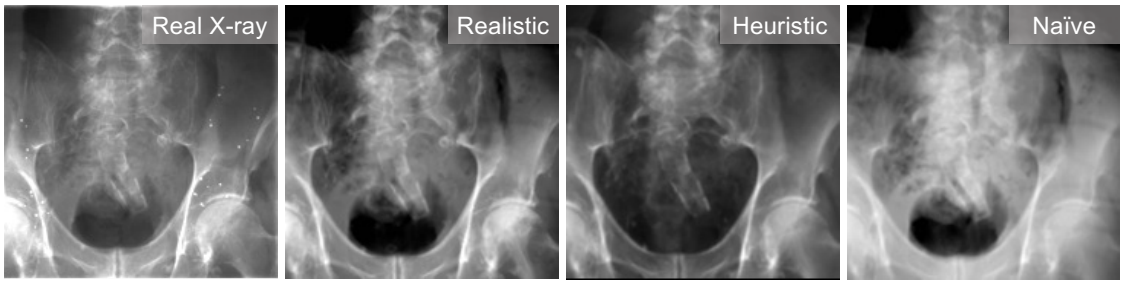
Ablation Simulators



DeepDRR[23]

- 3D Organ Segmentation
- Specified Attenuation
- Photon Spectrum
- Noise Sampling and Scattering

Xreg DRR[24]

- Simple Thresholding
- Noise Sampling

Naïve DRR

- Only line integration

[23] Unberath, M., Zaech, J.N., Lee, S.C., Bier, B., Fotouhi, J., Armand, M. and Navab, N., 2018, September. DeepDRR–a catalyst for machine learning in fluoroscopy-guided procedures. In International Conference on Medical Image Computing and Computer-Assisted Intervention (pp. 98-106). Springer, Cham.

[24] https://github.com/rg2/xreg

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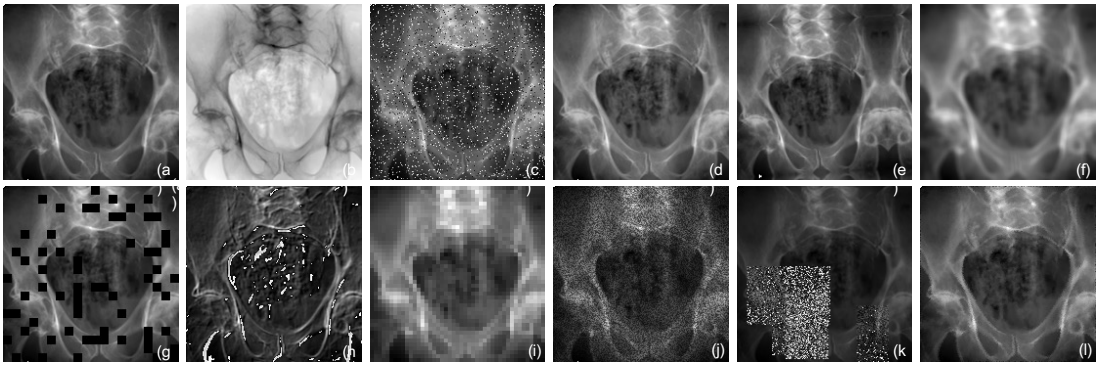
Domain Randomization

- Regular DR: Gaussian noise; Contrast; Random Crop
- Strong DR:



(a) No DR. (b) Inverting. (c) Pepper and salt noise injection. (d) Contrast. (e) Affine transform. (f) Blurring. (g) Dropout. (h) Sharpening and embossing. (i) Pooling. (j) Element-wise multiplication. (k) Box corruption. (l) Elastic effect.

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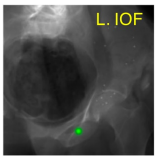
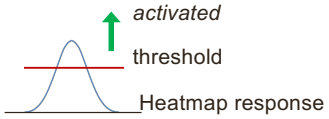
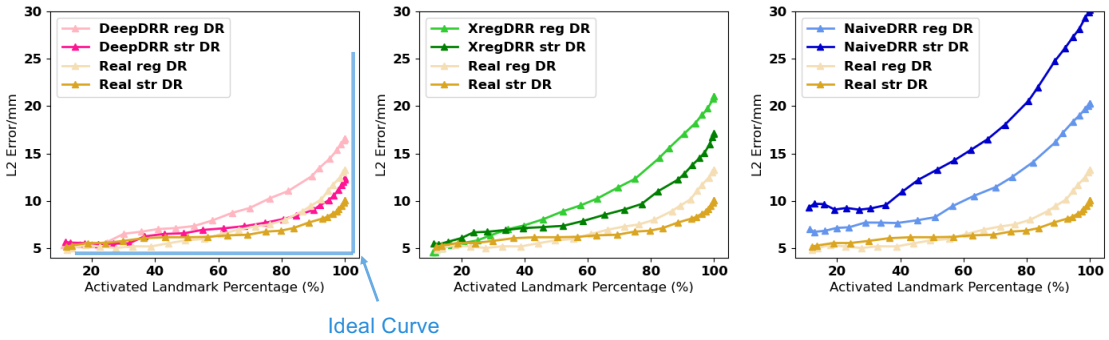
Landmark Detection Result – Domain Randomization







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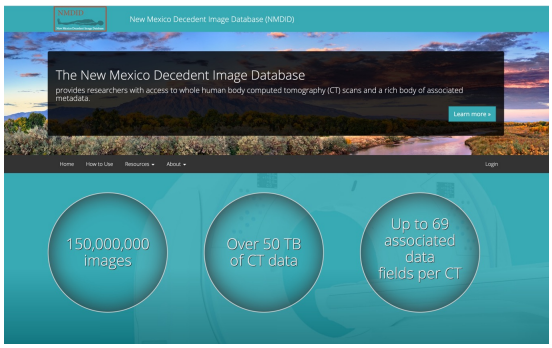
Scaled-up Simulation

- Annotated 20 CT scans from the New Mexico Decedent Image Database[24]
- Simulate 10k X-rays
- More sampled geometries



[24] Edgar, HJH; Daneshvari Berry, S; Moes, E; Adolphi, NL; Bridges, P; Nolte, KB (2020). New Mexico Decedent Image Database. Office of the Medical Investigator, University of New Mexico. doi.org/10.25827/5s8c-n515.

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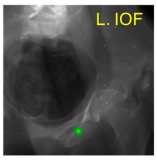
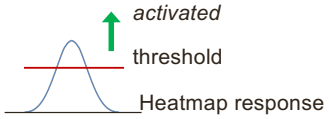
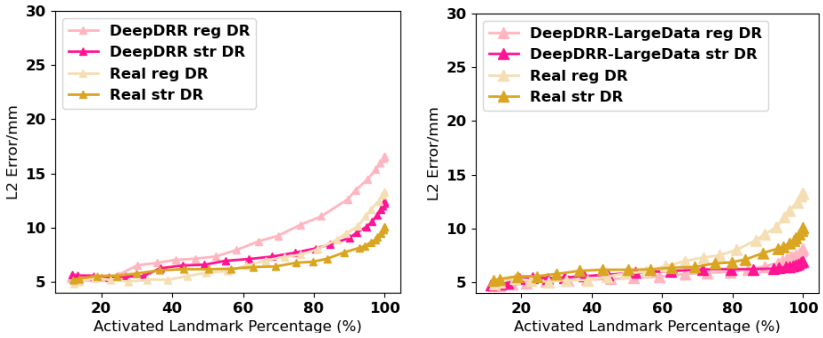
Landmark Detection Result – Scaled Up







Scaled-up simulation training outperforms Real2Real!

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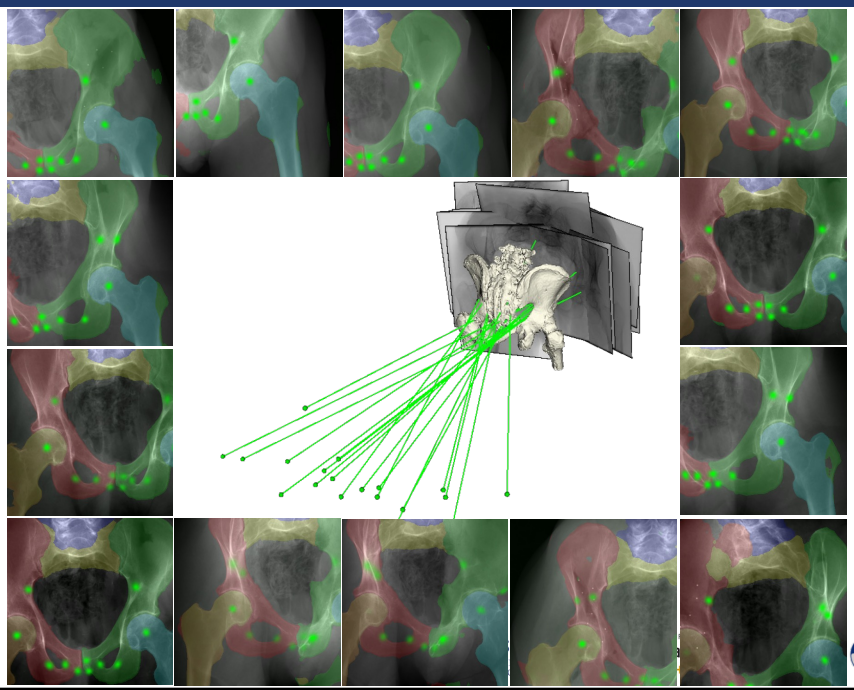
Qualitative Results of Sim2Real Detection Results



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Surgical Tool Detection Downstream Task

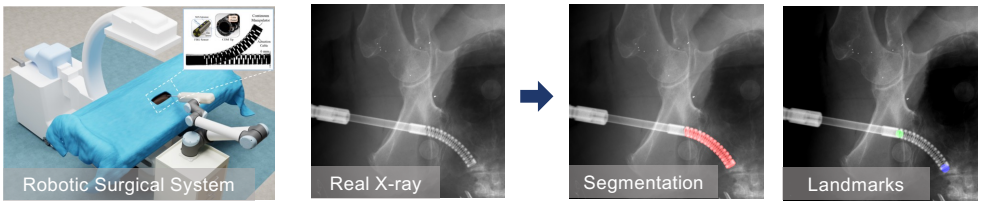

Table: Detection Accuracy

	Landmark Error (mm)	Dice Score
Sim2Real	2.13 ± 2.27	0.860 ± 0.115
Real2Real	1.90 ± 5.49	0.406 ± 0.194

- Real2Real was trained on 200 annotated X-ray images, Sim2Real was trained using 20k synthetic images

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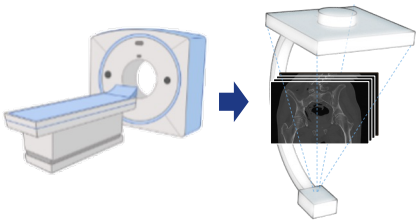
Conclusion and Contributions

- We **quantified the role of domain shift** in the deterioration of machine learning model performance from training in simulation to deployment on real data
- Physics-based Realistic Simulation with DR generalizes the best. Scaling up simulation dataset even outperforms Real2Real.
- SyntheX as a promising alternative for machine learning X-ray imaging tasks



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Acknowledgment

Mr. Benjamin Killeen: Contributed to comparison experiment running

Mr. Yicheng Hu: Contributed to simulation geometry calibration and experiment running

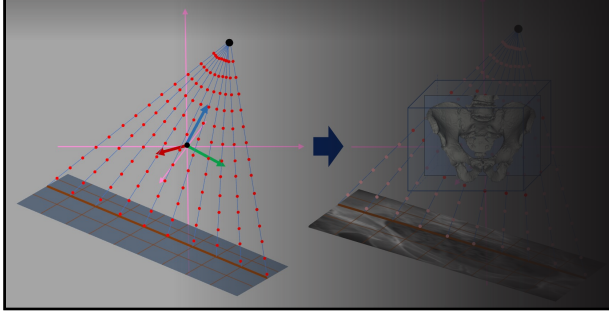
Dr. Robert Grupp: Collected and published the pelvic dataset

Related Publications/Manuscripts:

- **Gao, C.**, Killeen, B.D., Hu, Y., Grupp, R.B., Taylor, R.H., Armand, M. and Unberath, M., 2022. SyntheX: Scaling Up Learning-based X-ray Image Analysis Through In Silico Experiments. Under Review of Nature Machine Intelligence

Part II – Machine Learning Investigations

ProST: Projective Spatial Transformers



Recap: 2D/3D Registration Challenge

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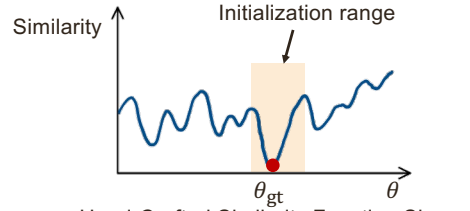
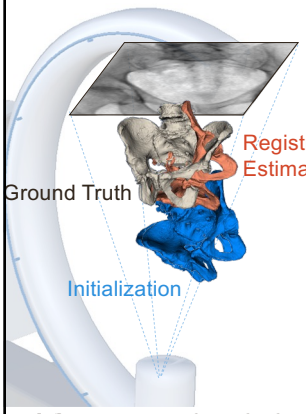
Narrow Capture Range

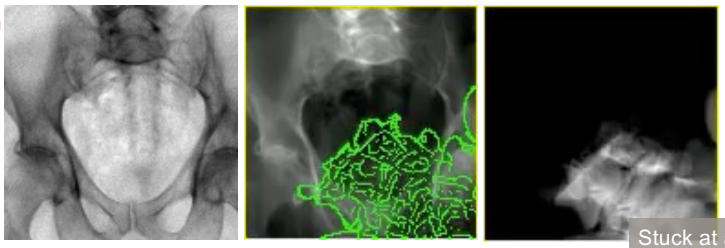
- Local minima of conventional hand-crafted similarity function, such as Grad-NCC
- Requires the initialization close to the ground truth



Hand-Crafted Similarity Function Shape



Conventional Intensity-based 2D/3D Registration Strategy:
- CMAES + Patch-based Grad-NCC[25]


Target X-ray Registration Movie

Stuck at a local minimum!

[25] Grupp, R.B., Armand, M. and Taylor, R.H., 2018. Patch-based image similarity for intraoperative 2D/3D pelvis registration during periacetabular osteotomy. In CARE Workshop of MICCAI 2018.

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Related Work

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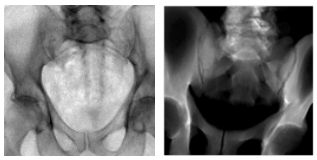
Pose Regression Methods

Limitations:

- Learning a mapping function from 2D projections is **an ill-posed problem**, which is prone to **strongly overfit to training domain**
- **Direct pose regression is unconstrained**, which can change dramatically if the input image appearance has a tiny difference


Target X-ray DRR

CNN Encoder

$\theta \in \mathrm{SE}(3)$

High-level Prototype

[26] Miao, S., Wang, Z.J. and Liao, R., 2016. A CNN regression approach for real-time 2D/3D registration. IEEE transactions on medical imaging, 35(5), pp.1352-1363.

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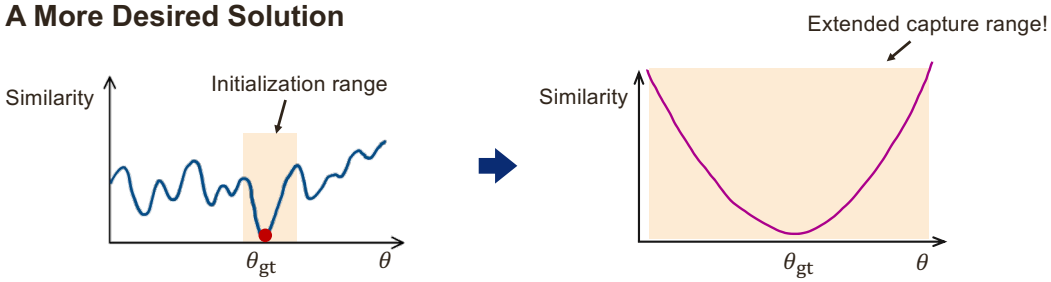
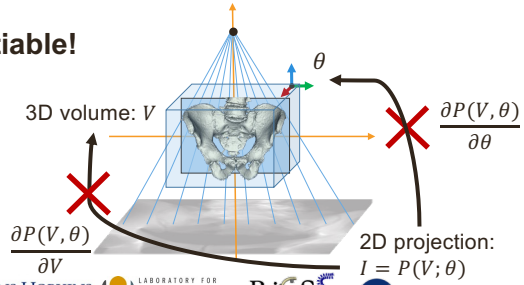
Motivation

A More Desired Solution



Traditional DRR Projector is not Differentiable!

- Oversized system matrix $A(\theta)$ to fit in memory
- Conventional optimization strategies are numeric-based methods, such as CMAES



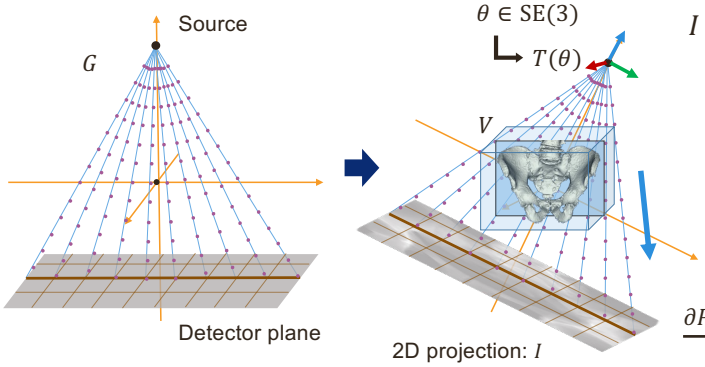
[27] Hansen, N., Müller, S.D. and Koumoutsakos, P., 2003. Reducing the time complexity of the derandomized evolution strategy with covariance matrix adaptation (CMA-ES). Evolutionary computation, 11(1), pp.1-18.

Projective Spatial Transformers (ProST)

ProST -- Differentiable DRR Operator

Spatial Sampling Grid: G

- Follows projection geometry



Given a pose parameter θ and 3D volume V as input, the DRR projection is:

$$I = P(V,\theta)$$
$$= \text{sum}(\text{interp}(V, T(\theta)G))$$

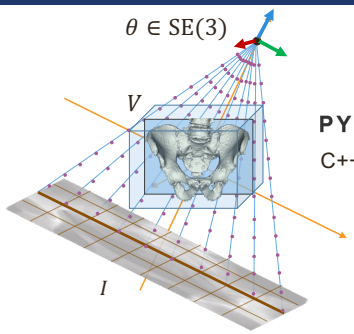
Linear transformation
Linear interpolation
Summation along the projection direction

Breakthrough:

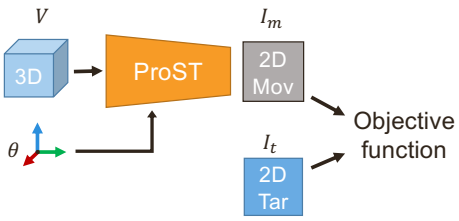
$\frac{\partial P(V,\theta)}{\partial \theta}$ $\frac{\partial P(V,\theta)}{\partial V}$ are differentiable!

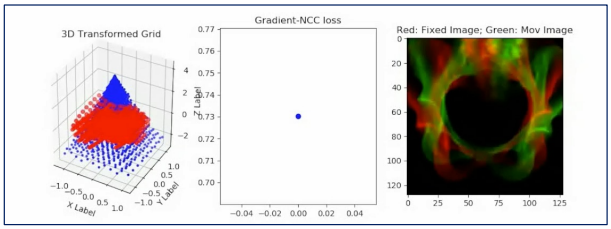
[28] **Gao, C.**, Liu, X., Gu, W., Killeen, B., Armand, M., Taylor, R., & Unberath, M. (2020, October). Generalizing spatial transformers to projective geometry with applications to 2D/3D registration. In International Conference on Medical Image Computing and Computer-Assisted Intervention (pp. 329-339). Springer, Cham.

Projective Spatial Transformers (ProST)



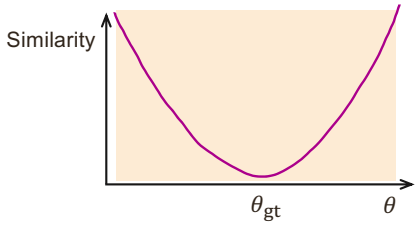
PYTORCH
C++, CUDA backend





Example registration using Grad-NCC similarity, optimized by PyTorch built-in SGD optimizer

How do we learn a better similarity function?



Network Similarity Function Shape

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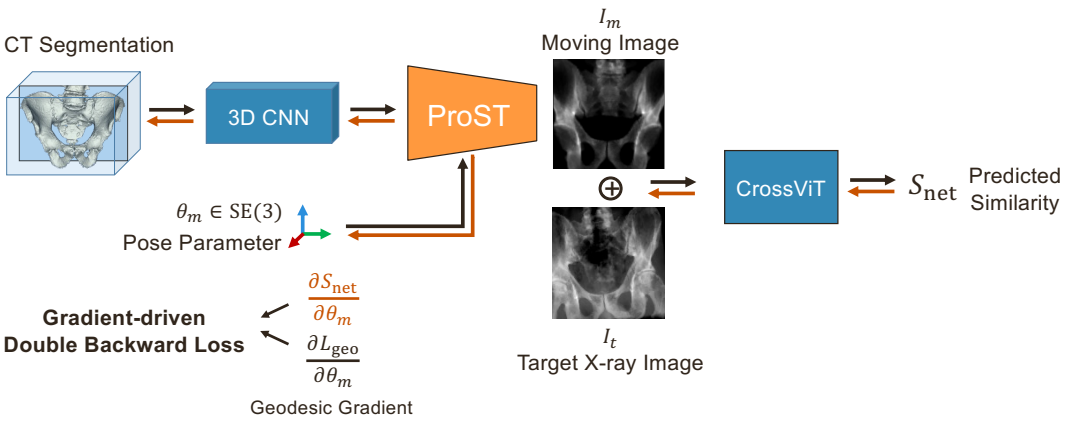
ProST 2D/3D Registration Pipeline

Target Similarity Function -- Geodesic Loss

- A convex objective function with respect to SE(3) pose parameters



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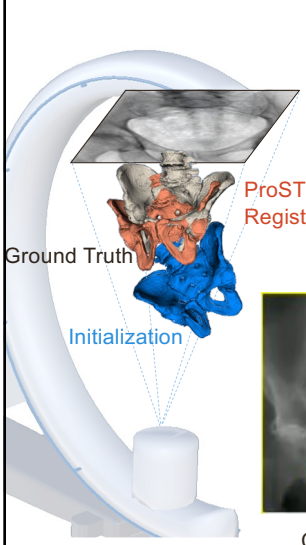
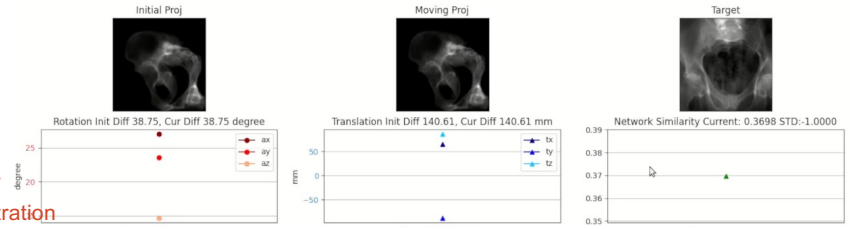
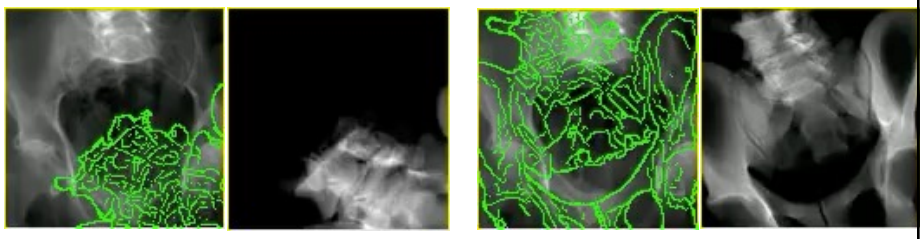
Example Registration using ProST Architecture

ProST Registration using Learned Similarity Function





ProST Registration brings the 3D object much closer to the ground truth pose



CMAES Start from Initialization (blue)

CMAES Start from ProST (orange)

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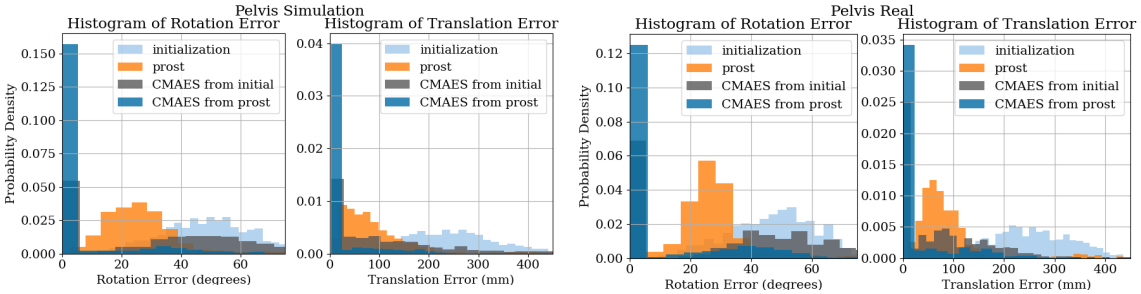
Experiments and Results

- Our pipeline was trained using 19 CT scans, evaluated on 1,000 synthetic X-rays and 200 real X-rays



Success Rate (%): Mean Target Registration Error < 10 mm

	Simulation	Real
CMAES from Initialization	32.6	36.0
CMAES from ProST Registration	**82.6**	**73.2**

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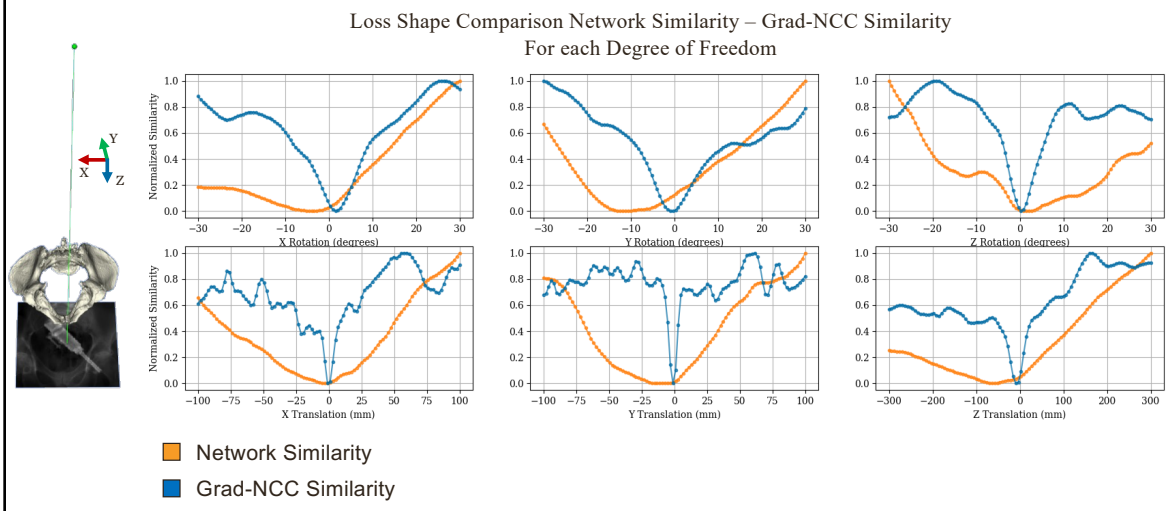
Experiments and Results



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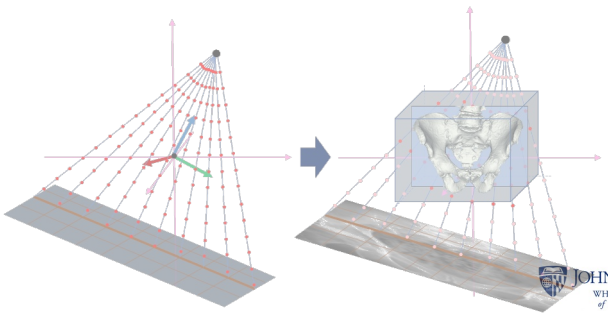
Conclusion & Contributions

- A novel ProST module, which enables differentiable volumetric rendering of X-ray images using CT volumes and analytical gradient calculation with respect to pose parameters.
- An innovative end-to-end 2D/3D image registration by learning a convex-shape similarity function.
- Demonstrated that ProST registration largely extends the conventional CMAES registration capture range.



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Acknowledgment

Dr. Xingtong Liu: Contributed to ProST design, registration architecture design, and double backward loss.

Ms. Anqi Feng: Contributed to data processing and comparison experiments in extended journal submission

Mr. Wenhao Gu and Mr. Benjamin Killeen: Provided valuable suggestions

Related Publications/Manuscripts:

- **Gao, C.**, Liu, X., Gu, W., Killeen, B., Armand, M., Taylor, R., & Unberath, M. (2020, October). Generalizing spatial transformers to projective geometry with applications to 2D/3D registration. In International Conference on Medical Image Computing and Computer-Assisted Intervention (pp. 329-339). Springer, Cham.
- **Gao, C.**, Feng, A., Liu, X., Taylor, R.H., Armand, M. and Unberath, M., 2022. A Fully Differentiable Framework for 2D/3D Registration and the Projective Spatial Transformers. Ready in submission to TMI

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Summary, Future Work Outlook and Acknowledgment

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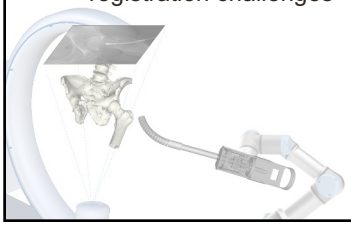
Summary

Effective Navigation System

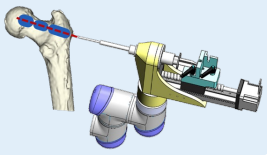
- Use purely fluoroscopic images
- (Semi-) Automatic registration algorithms
- Robot system-level validation
- Feasibility on variant clinical applications

Novel AI Frameworks

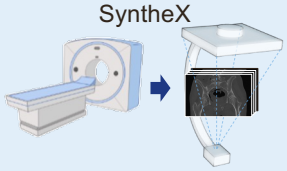
- Benefit machine learning X-ray imaging research
- Provide solutions to solve fundamental registration challenges



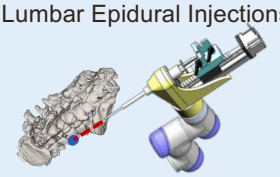
Femoroplasty



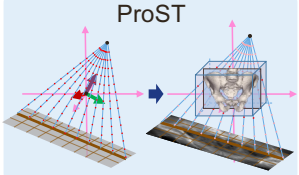
SyntheX



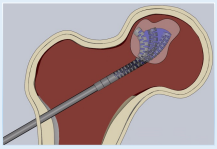
Lumbar Epidural Injections



ProST



Core Decompression



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Future Work Outlook

Optimal C-arm view geometry

- The best view that the registration has the highest chance to succeed

Patient Motion Verification

- Automatically detect patient motion and correct registration

Registration Uncertainty

- Confidence of the registration pose estimations

Image from https://dashtechinc.com/operating-room-of-the-future-dash-transforming-todays-challenges-into-tomorrows-opportunities/

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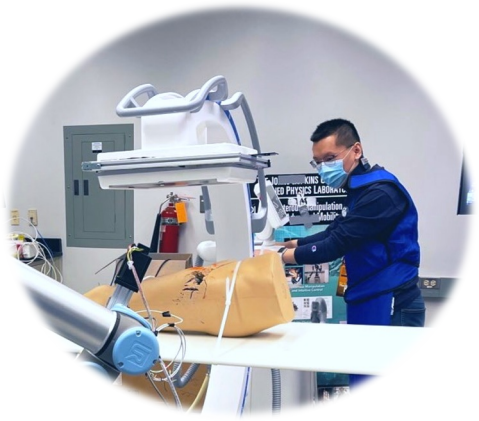
Thank you!



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