

# Methods for Autonomous Measurement of 3D Joint Kinematics from 2D Fluoroscopic Images

A Dissertation Defense

---

Andrew Jensen

March 4, 2024

# Outline

## Background

## Aims

Aim 1 - Joint Track Machine Learning

Aim 2 - Correcting Symmetric Implant Ambiguity

Aim 3 - Musings on a “Kinematics Translator” and Synthetic Kinematics Data

Aim 4 - This will definitely work on shoulders, right?

## Conclusion

## References

# A PhD...offense?



THE BEST THESIS DEFENSE IS A GOOD THESIS OFFENSE.

Henry Talbott  
@bathematician

The best PhD defense is a good PhD offense

Print out your doctoral committee's old theses beforehand and spend the first 30 minutes of your defense eviscerating them

2:38 PM · Jan 19, 2022

MODEL BASED 3D KINEMATIC ESTIMATION FROM 2D PERSPECTIVE SILHOUETTES:  
APPLICATION WITH TOTAL KNEE PROSTHESES

by

Scott Arthur Banks

B.S. Biomedical Engineering, Case Western Reserve University  
(1985)  
M.S. Biomedical Engineering, Case Western Reserve University  
(1988)

Submitted to the Department of Mechanical Engineering  
in Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy  
in Mechanical Engineering  
at the

Massachusetts Institute of Technology

June 1992

# A PhD...offense?

Wrist Biomechanics Influence Hand Function : Computer Simulations and Cadaveric Experiments of Nonimpaired and Surgically Salvaged Wrists.

Nichols, Jennifer A. >

[Dissertation Abstracts International 76-02B\(E\).](#) >

The wrist is a complicated joint that implant technology has failed to effectively replicate. As a result, salvage procedures are used to treat wrist osteoarthritis. Salvage procedures successfully relieve osteoarthritic pain by removing, fusing, and repositioning the carpal bones of the wrist. These drastic, geometric changes result in long-term impairments in hand function. How salvage procedures, which specifically alter the wrist, result in hand impairments is not understood.

A PhD...offense?

**Simulation and experimental analyses to assess walking performance  
post-stroke using step length asymmetry and module composition**

**by**

**Jessica Lynn Allen, B.S.M.E.; M.S.E.**

**Dissertation**

Overall Knee Joint Loading Exposure And Clinical Progression Of Knee  
Osteoarthritis

by

Kerry Elizabeth Costello

Submitted in partial fulfilment of the requirements  
for the degree of Doctor of Philosophy

A PhD...offense?

A FRAMEWORK FOR SPATIOTEMPORAL QUANTIFICATION OF NEURAL FUNCTIONAL  
CONNECTIVITY

By

CATIA SOFIA PINHO DA SILVA

## Acknowledgments

I would like to thank the McJunkin Family Charitable Foundation for their generous grant that supports this work.

# The Problem

- By 2030, roughly 3.5 million Total Knee Arthroplasty (TKA) will be performed in the US [1].
- 20% of patients receiving TKA are dissatisfied.
  - Instability, pain, unnatural [2, 3, 4].
- No reliable method of clinically assessing and quantifying joint dynamics.
  - Human supervision
  - Time consuming
  - Specialized equipment



# Our Proposition

Orthopaedic surgeons and clinicians would readily adopt a **practical** and **inexpensive** technology that allows them to **measure** a patient's joint kinematics during **activities of daily living**.



# Constraints

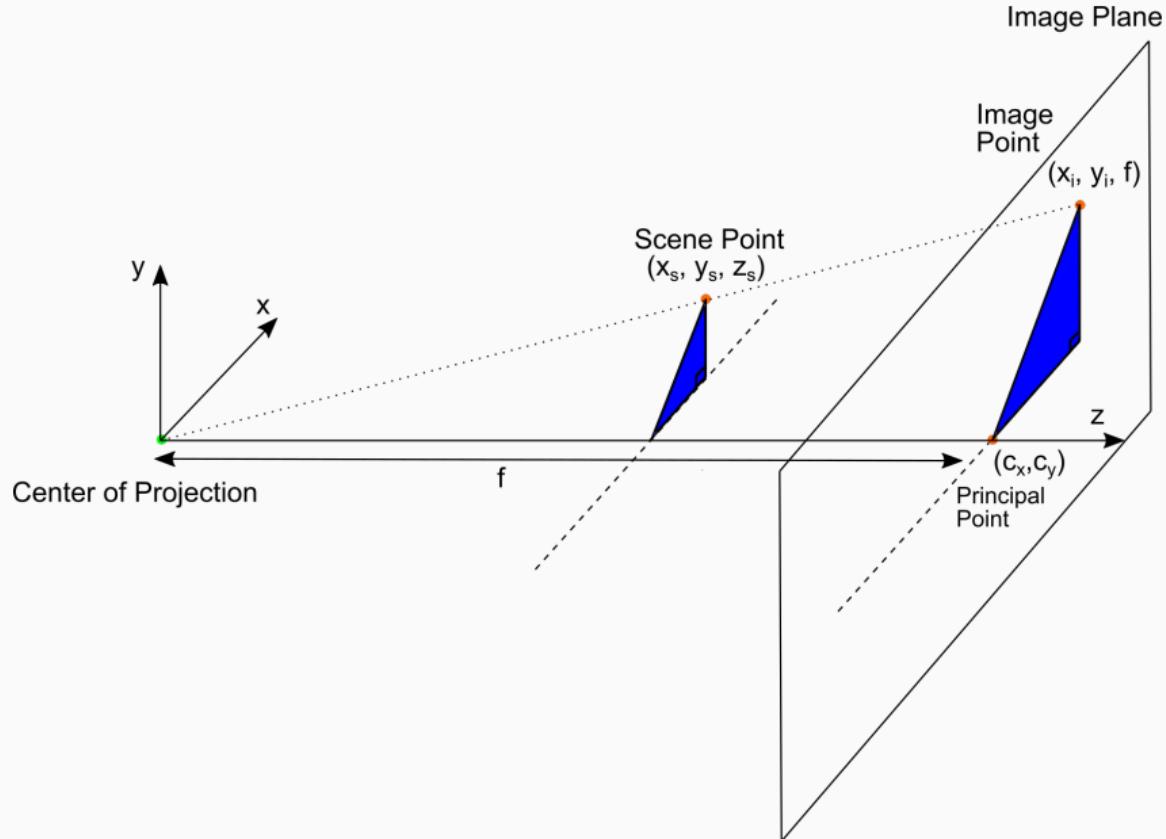
- It must fit within a **standard clinical workflow**
- The technology must utilize equipment **commonly found in hospitals**
- There must not be significant **human supervision** nor interaction to generate an examination report.



## Background

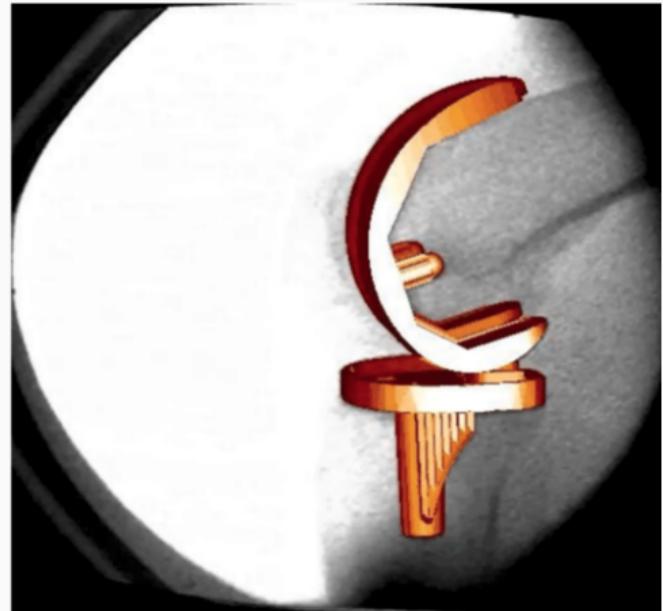
---

## Background - Projective Geometry



## Background - Model-Image Registration

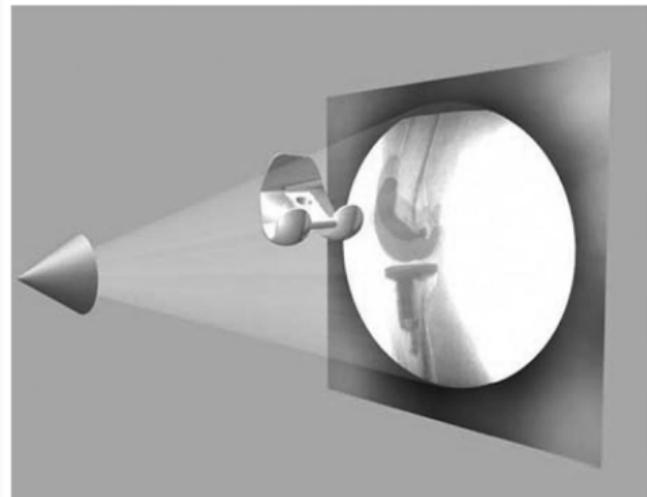
If we know the projective parameters of the fluoroscopy machine, can we tinker with  $T_{implant}^{cam}$  so that our virtual projection matches the fluoroscopic image?



From [5]

## Background - Model-Image Registration

If we know the projective parameters of the fluoroscopy machine, can we tinker with  $T_{implant}^{cam}$  so that our virtual projection matches the fluoroscopic image?



From [5]

## Historical Overview

Many different approaches have attempted to solve the model-image registration problem.

- Pre-computed projections
- Skin-mounted motion Capture
- Biplane Imaging
- Iterative Projections
- Roentgen Stereophotogrammetry

# Pre-Computed Projections

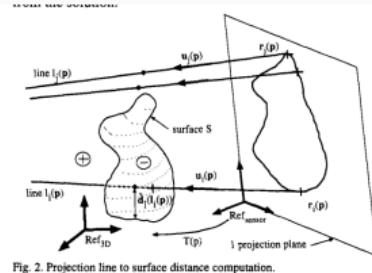
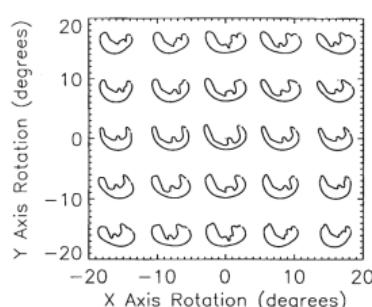


Fig. 2. Projection line to surface distance computation.

- Saving space and memory by pre-computing as much as possible.
- Pre-computed distance maps [6, 7].
- Pre-computed shape libraries [8]

From [7]



From [8]

# Limitations of Pre-Computed Projections

- Requires an accurate contour from the input image in order to perform calculations.
  - Human supervision for isolated contour
  - Inaccuracy with naive edge detection

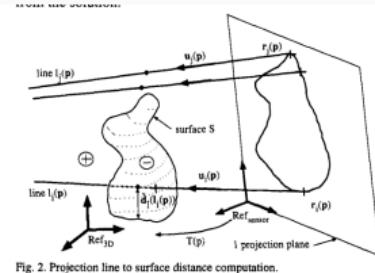
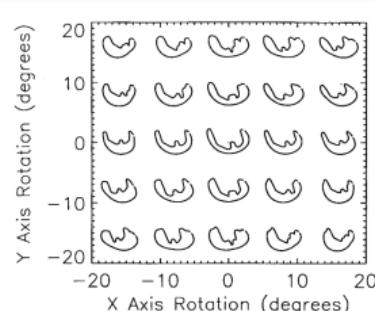


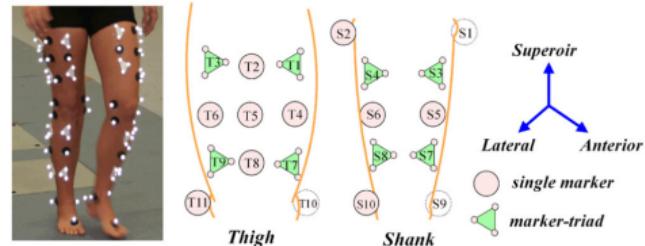
Fig. 2. Projection line to surface distance computation.

From [7]



From [8]

# Motion Capture (MoCap)



- Can measure motion of MoCap beads very accurately.
- Skin-mounted [9, 10, 11].
- Bone pins [12].

From [9]

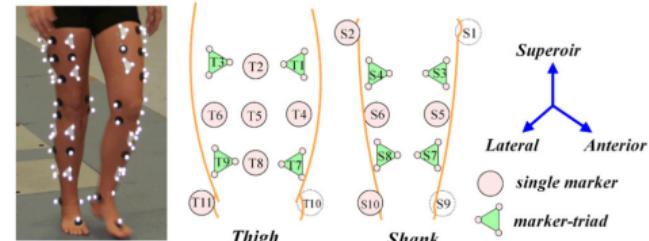


From [12]

# Limitations of Motion Capture

## Skin Mounted

- Doesn't accurately describe underlying skeletal motion with clinical accuracy [9, 10, 11].



From [9]

## Bone Pins

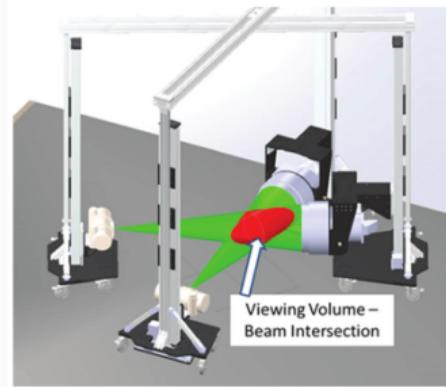
- Any volunteers?



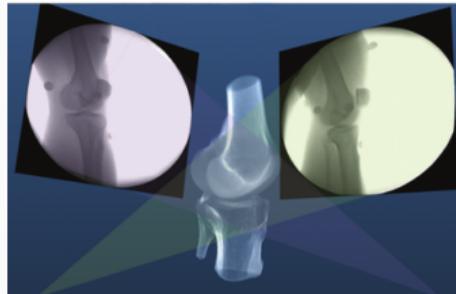
From [12]

# Biplane Imaging

- Utilizes multiple cameras to resolve 3D position and orientation[13, 14].
  - Highly accurate.
  - Gold Standard.

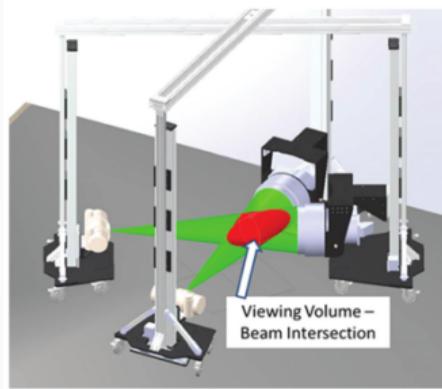


Both from [13]

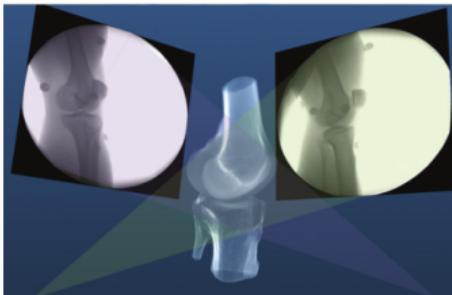


# Limitations of Biplane Imaging

- Not many hospitals have biplane fluoroscopy setups.
- Clinically impractical

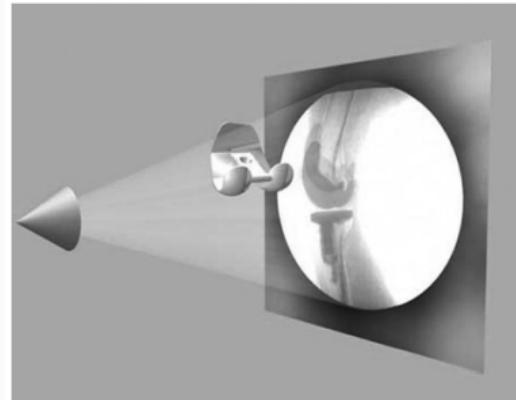


Both from [13]



# Iterative Projections

- Take advantage of modern computational graphics pipelines to quickly perform projection matching.
  - Image/Intensity similarity metrics [5]
  - Feature/Contour similarity metrics [15]



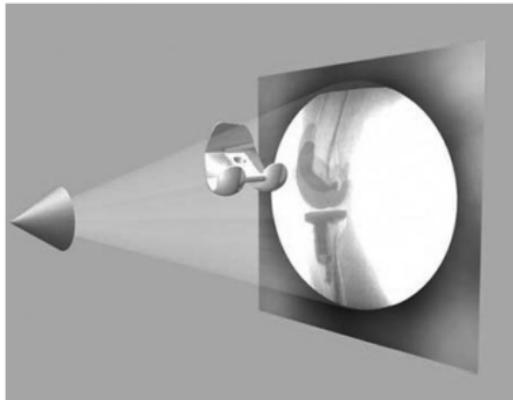
From [5]



From [15]

## Limitations of (historic) Iterative Projection Methods

- Requires human supervision for:
  - Pose initialization
  - Escaping local minima
  - Implant detection
- Chaotic and Noisy objective function



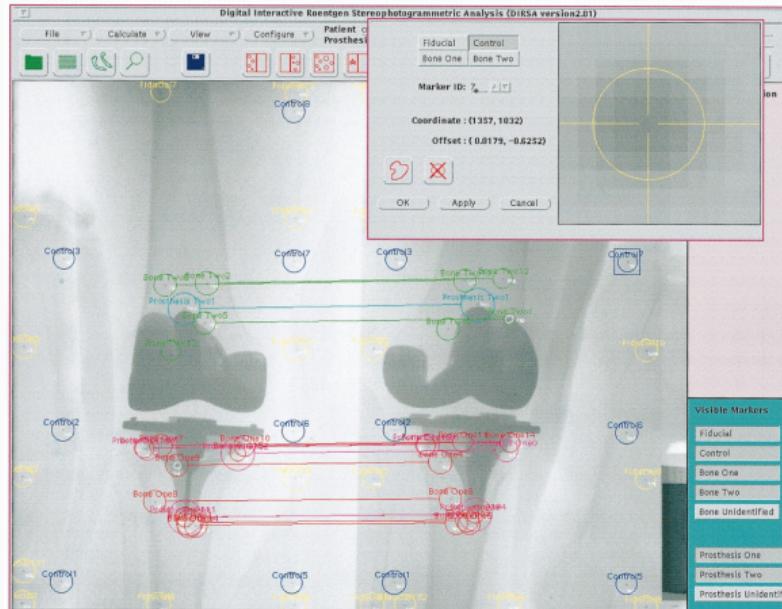
From [5]



From [15]

# Roentgen Stereophotogrammetry (RSA)

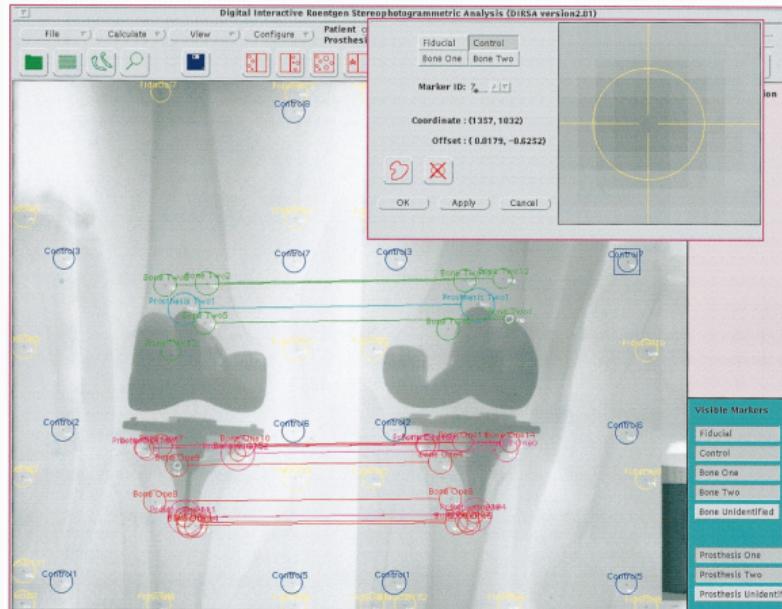
- Uses implanted tantalum beads for motion tracking [16, 17]
- Extremely accurate [18, 19]
- Gold standard Measurement [20]



From [16]

# Limitations of RSA

- Involves additional surgical procedures for inserting tantalum beads.
- Human supervision
- Bi-plane imaging



From [16]

## Aims

---

## Aims

**Aim 1:** Joint Track Machine Learning: An Autonomous Method of Measuring Total Knee Arthroplasty Kinematics From Single-Plane X-Ray Images<sup>1</sup>

**Aim 2:** Correcting Symmetric Implant Ambiguity in Measuring Total Knee Arthroplasty Kinematics from Single-Plane Fluoroscopy<sup>2</sup>

**Aim 3:** Some Musings on a “Kinematics Translator” and Synthetic Kinematics Data

**Aim 4:** This will definitely work on shoulders, right?<sup>3</sup>

---

<sup>1</sup>Published in the Journal of Arthroplasty [21]

<sup>2</sup>In Revision for Publication in the Journal of Biomechanics

<sup>3</sup>In Review for Publication in the Journal of Computers in Biology and Medicine

## Background

## Aims

Aim 1 - Joint Track Machine Learning

Aim 2 - Correcting Symmetric Implant Ambiguity

Aim 3 - Musings on a “Kinematics Translator” and Synthetic Kinematics Data

Aim 4 - This will definitely work on shoulders, right?

## Conclusion

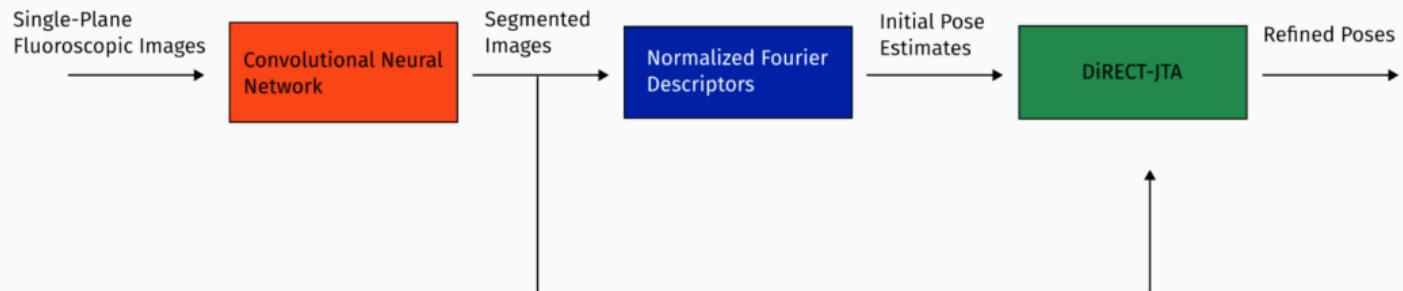
## References

## Goal

Demonstrate the feasibility of a fully autonomous, model-image registration pipeline.

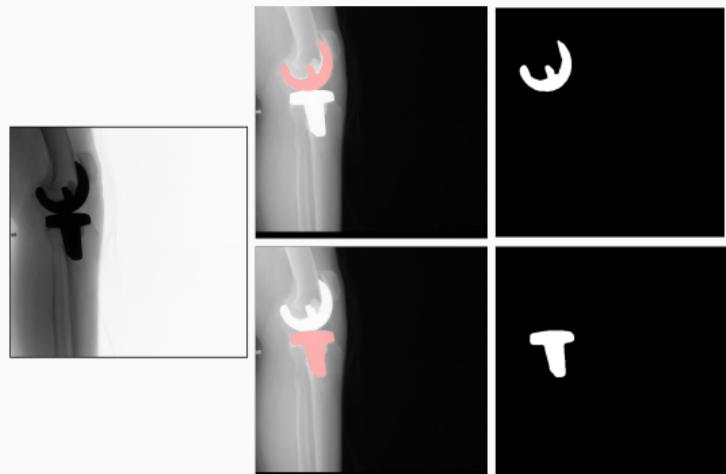
# Method

- Three-tiered approach
  - Convolutional Neural networks (CNN) for autonomous implant detection
  - Normalized Fourier Descriptor shape libraries
  - Robust contour-based global optimization scheme



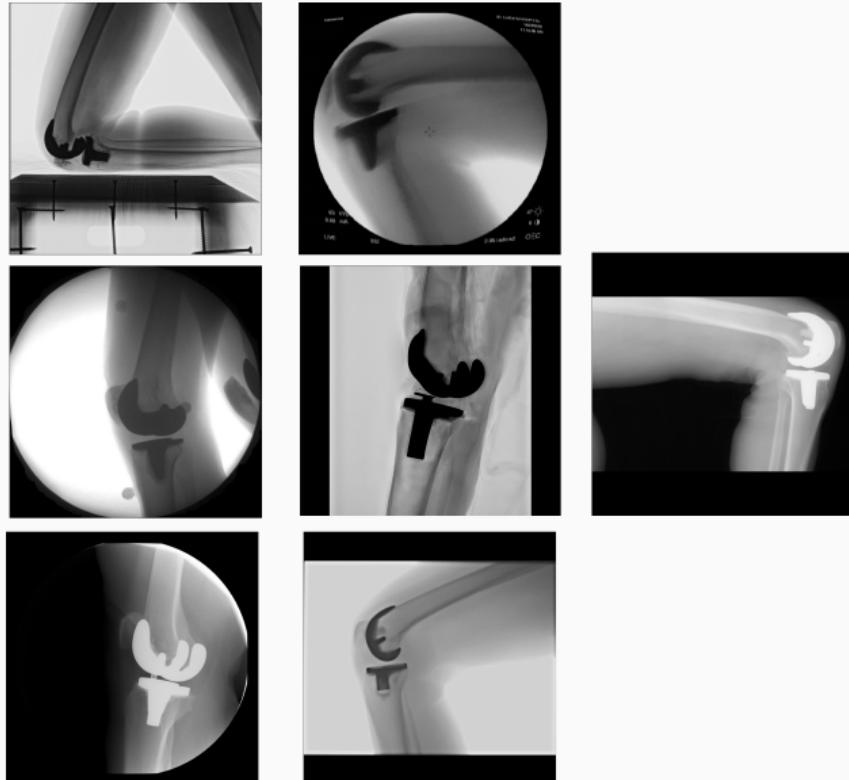
# Autonomous Implant Detection Using Convolutional Neural Networks

- 2 CNNs
  - Femoral and Tibial implants
- High Resolution Network [22]



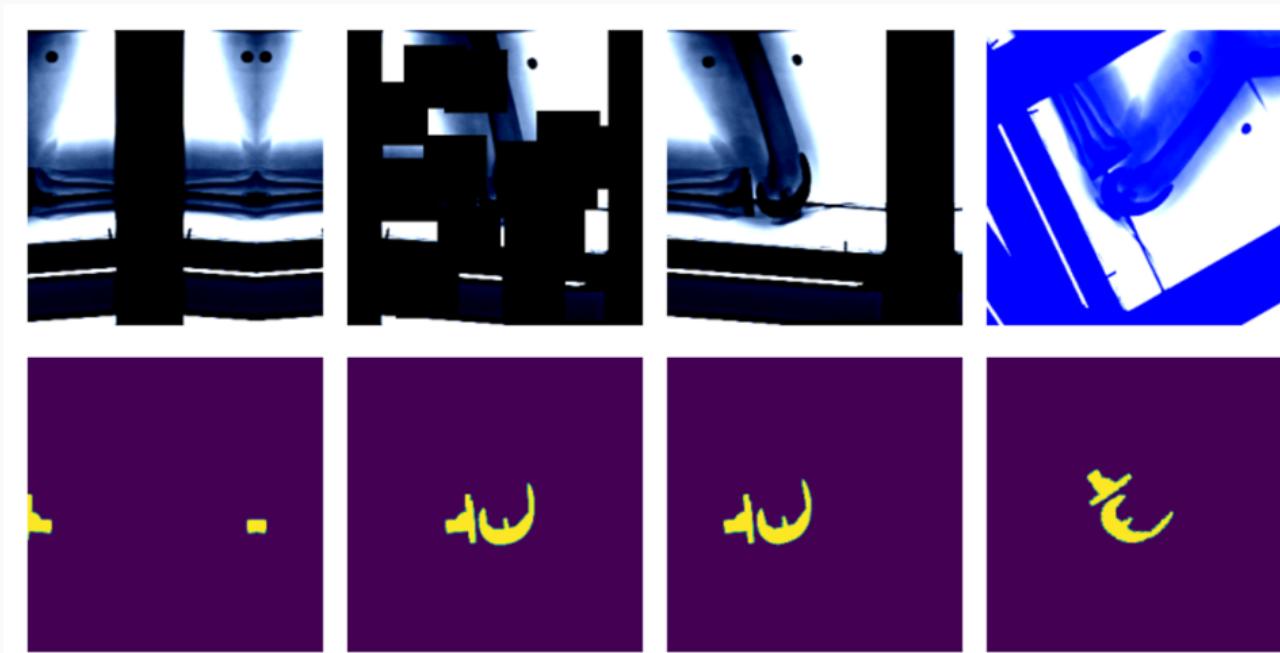
# Neural Network Data

- ~8000 images
  - 7 TKA kinematics studies
    - 71 subjects
    - 7 implant manufacturers
    - 36 distinct implants
    - Squat, lunge, knee, stair ascent



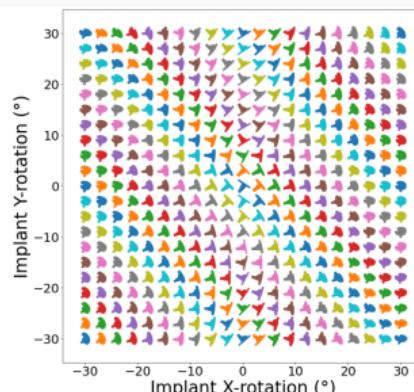
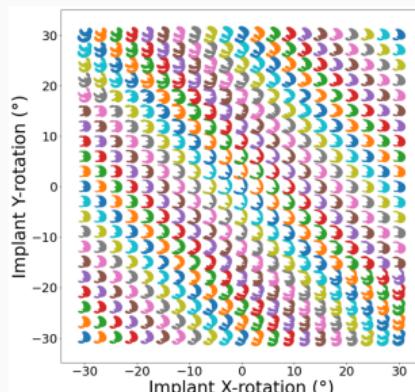
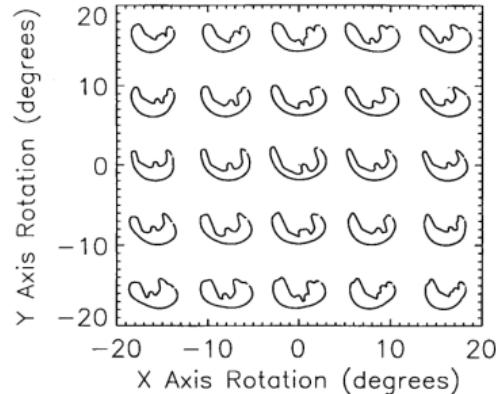
# Neural Network Robustness

- Additional augmentations introduced during training [23].



# Normalized Fourier Descriptor Shape Libraries

- Pose initialization using segmentation output.
- $\pm 30^\circ$  library span at  $3^\circ$  increments.



# Pose Refinement Using Global Optimization

- Two main features
  - Objective function
  - Optimization routine

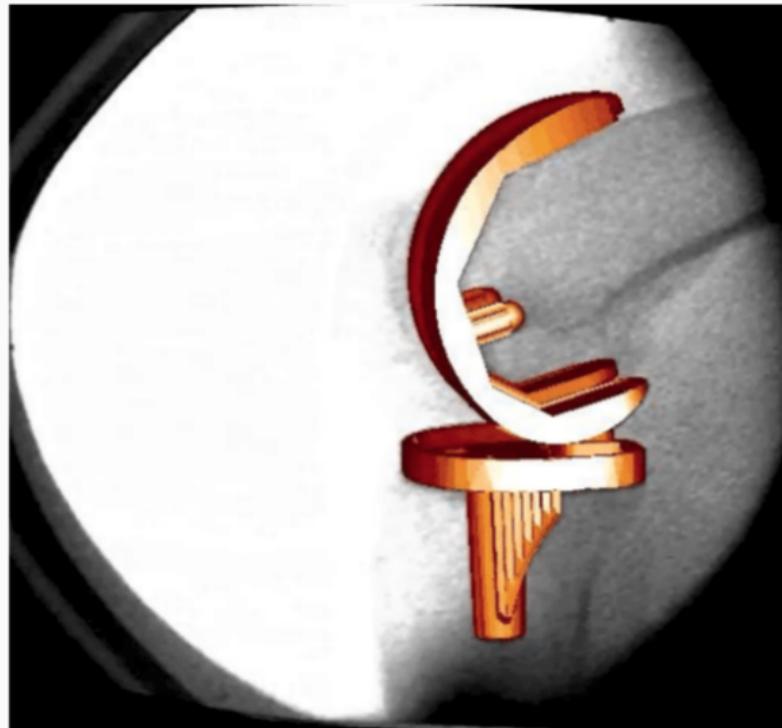
$$\operatorname{argmin}_x \{f(x) : x \in \Omega\}$$

## Contour-based Objective Function

- With accurate projection, contours provide a strong heuristic for orientation.
- Overlapping pixels between CNN segmentation and projected implant.
  - $L_1$  norm has quick parallel computation.

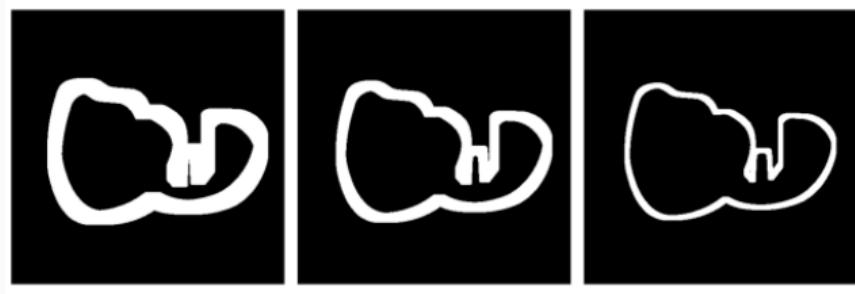
$$J = \sum_{i \in H} \sum_{j \in W} |I_{ij} - P_{ij}| = L_1(I, P)$$

- Sensitive to minor perturbations



# Improving Robustness

- Dilation decreases sensitivity to perturbations.
- Multi-stage optimization can reduce dilation back to original edges.

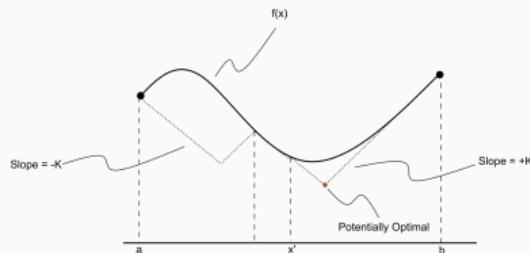
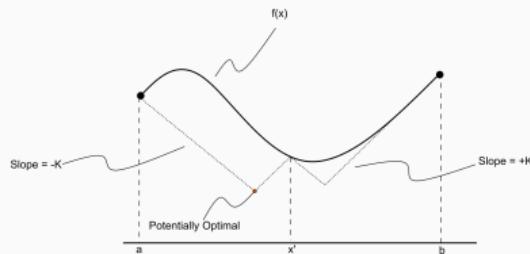
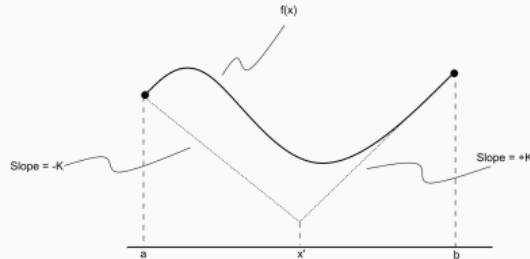


## Optimization Routine

- No analytic form of the objective function exists, it **must** be sampled at points of interest.
  - Black Box Optimization [24, 25]

# Lipschitzian Optimization

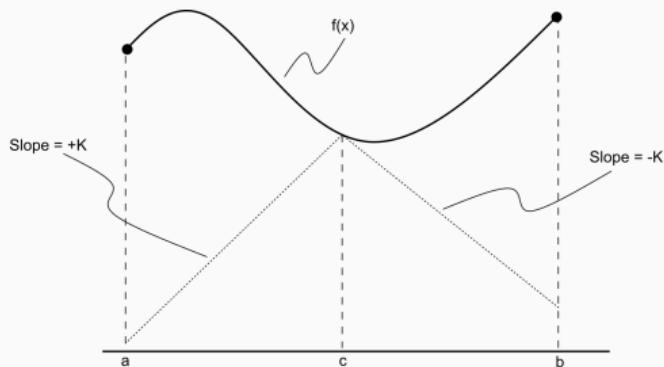
- Robust, global, black-box optimization routine if Lipschitz constant ( $K$ ) is known [26].
- Lipschitz constant bounds the rate of change of a function.
- What if you don't know the Lipschitz constant?



## Lipschitzian Optimization Without the Lipschitz Constant

D. R. JONES,<sup>1</sup> C. D. PERTTUNEN,<sup>2</sup> AND B. E. STUCKMAN<sup>3</sup>

- Sample end-points instead of intersecting lines.
- Potentially optimal regions based on value at center and total size.
  - Trisect potentially optimal regions and re-sample centers



# Trisecting Region

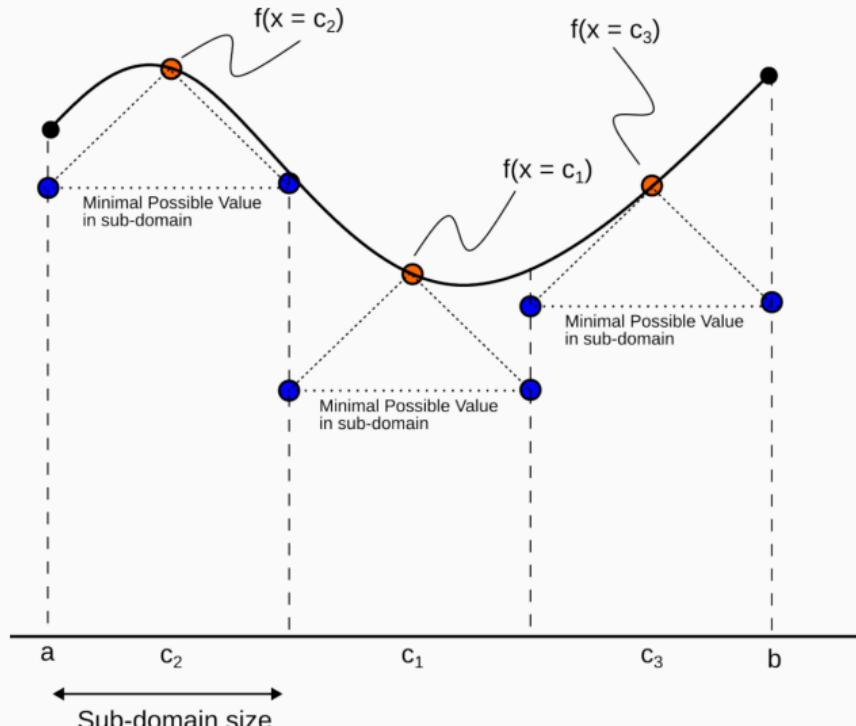
$$\begin{bmatrix} f(x = c_1) & d(c_1) \\ f(x = c_2) & d(c_2) \\ \vdots & \vdots \\ f(x = c_N) & d(c_N) \end{bmatrix}$$

Where

$f(x = c_i) \equiv$  Sampled function value

$d(c_i) \equiv$  Sub-domain size

for  $i \in [1, N]$



## Another Iteration

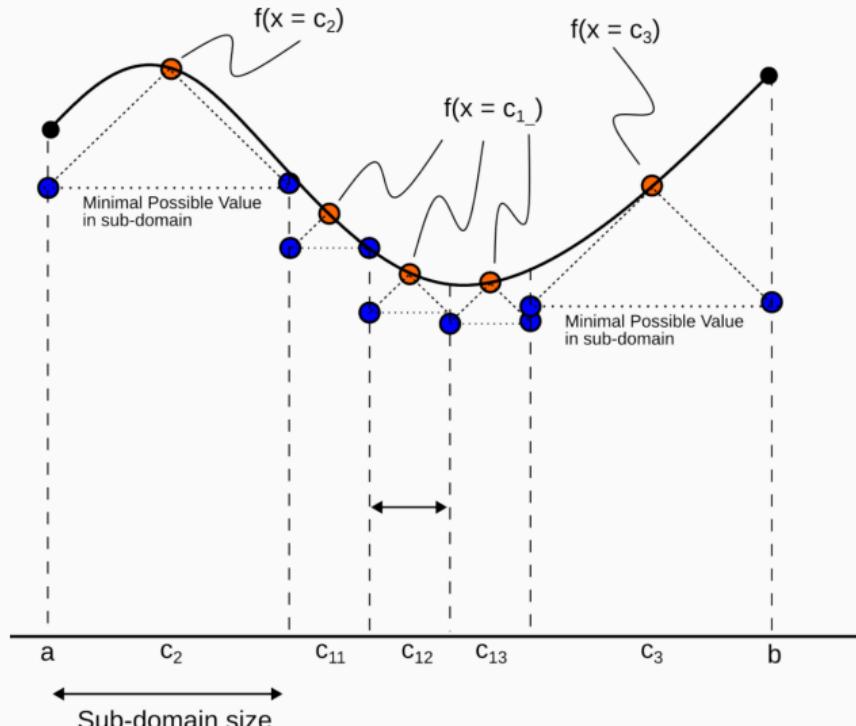
$$\begin{bmatrix} f(x = c_1) & d(c_1) \\ f(x = c_2) & d(c_2) \\ \vdots & \vdots \\ f(x = c_N) & d(c_N) \end{bmatrix}$$

Where

$f(x = c_i) \equiv$  Sampled function value

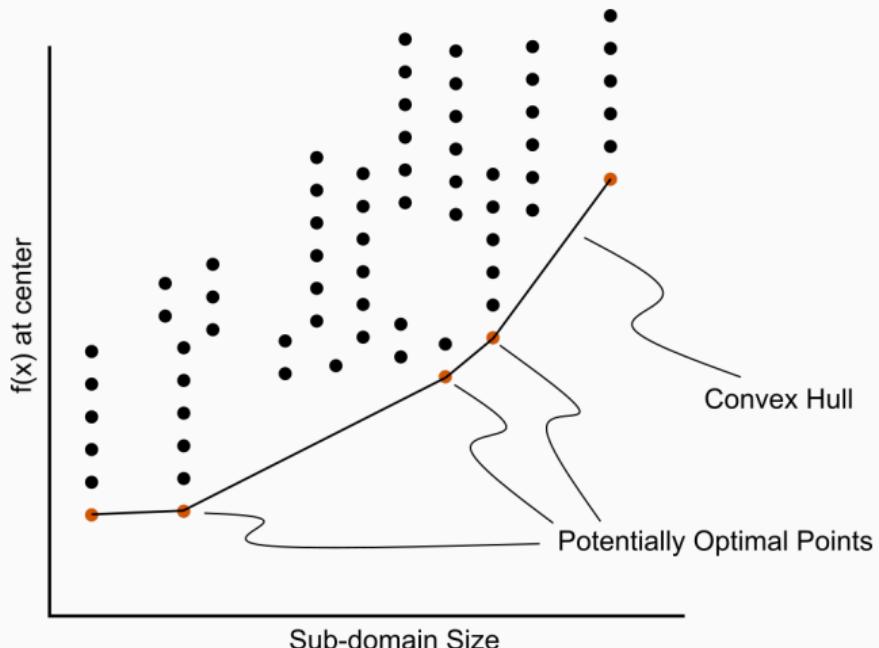
$d(c_i) \equiv$  Sub-domain size

for  $i \in [1, N]$



## Determining Potentially Optimal Regions

- Convex hull [27, 28, 29, 30] of region size vs. center value



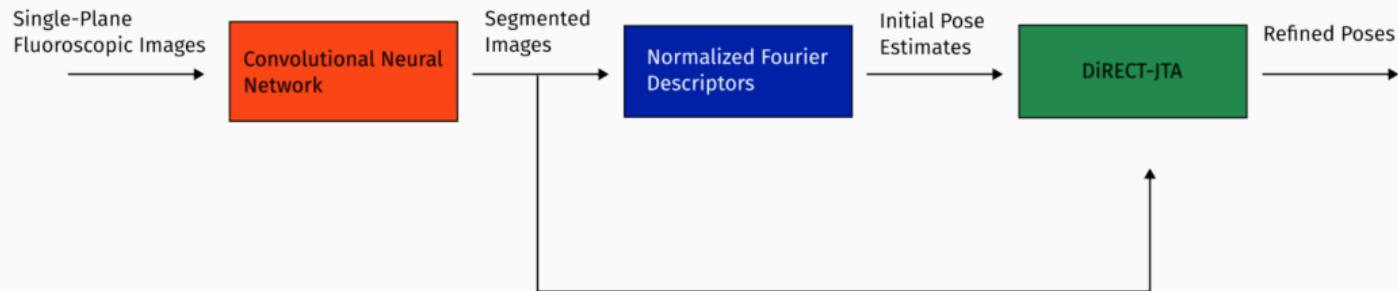
# DiRECT for Joint Track Machine Learning

- Search region is along all 6 degrees of freedom.
  - Normalize to  $[0, 1]$ .
- Three stages, each with decreasing levels of dilation.
  - Iteration budget for each stage.

Stage	Budget [Iterations]	Search Range [mm,deg]	Dilation (pixels)
“Tree”	~20,000	$\pm 45$	5
“Branch”	~20,000	$\pm 25$	3
“Leaf”	~10,000	$\pm 100$ ( $z_{trans}$ ) / $\pm 3$ ( <i>else</i> )	1

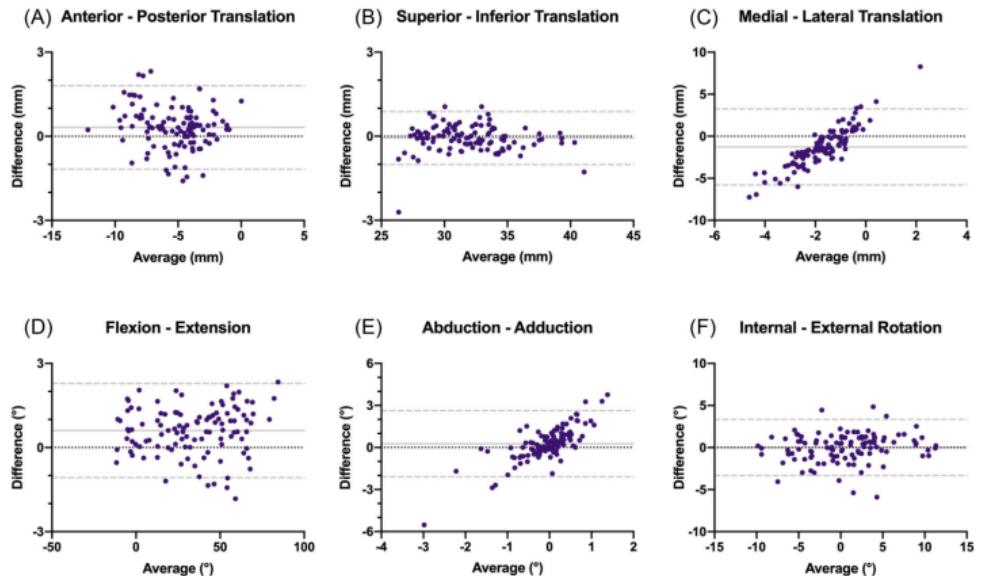
# Testing Performance

Now that we have our refined poses, how well does our system perform?



# Validation

- Independent research group using Model-Based RSA.
- Determine the level of concordance between the two measurement systems
  - Bland-Altman Plots
- Achieved clinically acceptable accuracy [20, 21].
- Highly repeatable



## Awards

The work presented in this aim won the HAP Paul Award for Best Paper from the International Society for Technology in Arthroplasty's 2022 Annual Meeting.



## Background

## Aims

Aim 1 - Joint Track Machine Learning

Aim 2 - Correcting Symmetric Implant Ambiguity

Aim 3 - Musings on a “Kinematics Translator” and Synthetic Kinematics Data

Aim 4 - This will definitely work on shoulders, right?

## Conclusion

## References

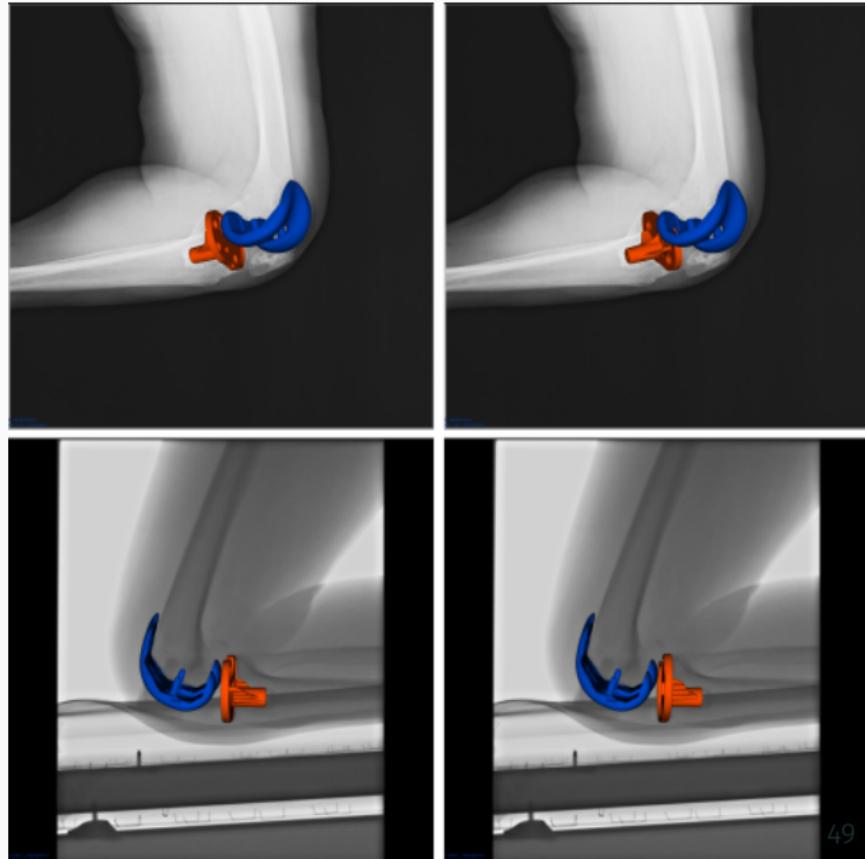
## Goal

- The goal of this aim is to validate and test methods that can overcome single-plane limitations for model-image registration.
  - Out-of-plane (OOP) Translation
  - Symmetry Traps

## Symmetry Traps

With a symmetric tibial implant, the contour is not always a perfect heuristic for true pose.

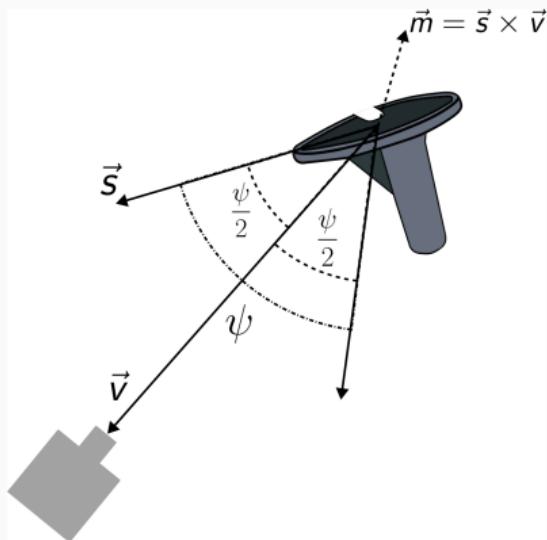
Found “ambiguous zone” within  $3^\circ$  of pure lateral pose with high propensity for symmetry traps [21].



## Solving the Symmetric Pose

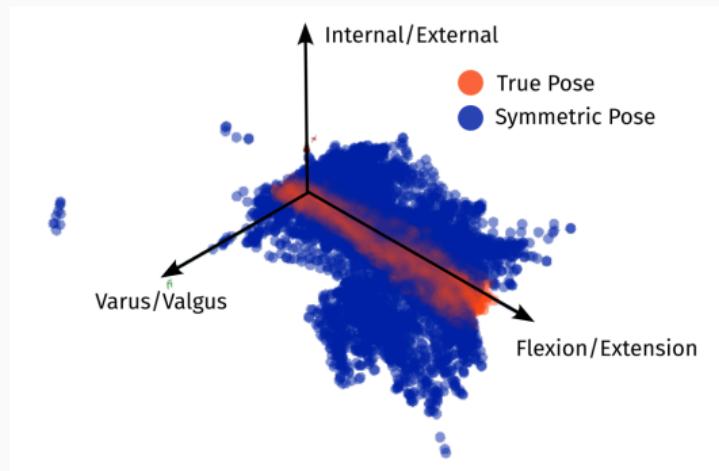
Algorithm devised to “flip” pose into symmetric counterpart.

1. Determine viewing ray from camera to implant centroid, denote  $\vec{v}$ , normalize.
2. Denote symmetric-plane normal vector  $\vec{s}$ , normalize.
3. Measure relative “off-lateral” orientation of implant,  $\cos(\theta) = \frac{\vec{v} \cdot \vec{s}}{||\vec{v}|| ||\vec{s}||}$
4. Apply body-centered rotation to implant about  $\vec{m} = \vec{s} \times \vec{v}$  by  $\psi = 2\theta$ .



## Methods - Training Set

- “Symmetric” poses for each of the 12,000 frames were calculated using the “flipper” algorithm, yielding ~24,000 total training samples. The input for each sample was  $[\theta_{F/E}, \theta_{V/V}, \theta_{I/E}, \psi]$ , and the output was one of {True, Symmetric}



The training data plotted with each axis representing an anatomical rotation (origin not to scale).

## Methods - Machine Learning

Using `scikit-learn`, the following classifiers were implemented:

- Support Vector Machine, K-Nearest-Neighbors, AdaBoost, Histogram Gradient Boosting, Bagging Estimator, Stacked Generalization, Majority Voting Classifier

## Methods - Fixing “Symmetry Traps”

For an input image sequence, the following is performed:

1. Each pose and its symmetric counterpart are fed into the machine learning classifier
  - 1.1 If the outputs are different, take the pose labeled “true” as the correct pose.
  - 1.2 If the outputs are the same, (i.e. both a pose and its symmetric counterpart return “true”), label image “ambiguous”
2. For all images that are NOT ambiguous, construct a cubic spline through the three rotation measurements.
3. For all images that are labeled “ambiguous”, determine which of the two poses is closer to the spline, and take that as the “correct” pose.

# Results - ML Classification

Table 1: Machine Learning Classifier Performance						
Classifier	Tuned Hyperparameters	Test Set	Accuracy (%)	Sensitivity (%)	Specificity (%)	F1-Score
Support Vector Machines (Radial Basis Function)	C = 1000	Internal External	92.1 <b>94.2</b>	94.8 97.1	89.7 91.6	0.92 <b>0.94</b>
Support Vector Machine (Polynomial Kernel)	C = 1000 Polynomial Degree = 2	Internal External	87.7 92.1	92.5 96.6	83.8 88.4	0.87 0.92
K-Nearest-Neighbors	Neighbors = 4 Distance Metric = Minkowski Weights = 'distance'	Internal External	93.1 90.9	94.0 93.6	92.3 88.6	0.93 0.91
AdaBoost	Num. Estimators = 200 Learning Rate = 1 Estimator = Decision Tree	Internal External	88.8 92.9	91.1 <b>97.2</b>	86.7 89.2	0.88 0.93
Histogram Gradient Boosting	Learning Rate = 0.1 Max Iterations = 100 Max Depth = None	Internal External	93.1 93.2	95.0 96.7	91.4 90.3	0.93 0.93
Bagging Estimators	Num. Estimators = 500	Internal External	93.3 93.8	94.3 96.0	92.4 <b>91.9</b>	0.93 0.94
Stacked Generalization	Estimator = Logistic Regression Cross Validation = 'prefit'	Internal External	<b>94.3</b> 92.9	94.8 94.9	<b>93.8</b> 91.0	<b>0.94</b> 0.93
Majority Voting Classifier	N/A	Internal External	92.6 93.3	<b>95.9</b> 96.9	89.9 90.3	0.92 0.93

## Results - Fixing “Symmetry Traps”

- Accuracy: 91.9%
- Sensitivity: 0.674
- Specificity: 0.940

The distribution of  $\psi$  for correct and incorrect frames was measured.

- Average  $\psi_{correct} = 16.6^\circ$ .
- Average  $\psi_{incorrect} = 7.12^\circ$ .

## Results - Stratified $\psi$ Correction Performance

**Table 2:** Stratified  $\psi$  Test Set Stacked Generalization Classification Performance

Psi Range	Sample Size	Accuracy (%)	Sensitivity (%)	Specificity (%)	F1-Score
0 – 5°	488	71.0	71.4	70.7	0.69
5 – 10°	1132	88.2	90.5	86.0	0.88
10 – 15°	1224	93.0	92.8	93.2	0.93
15 – 20°	1107	96.1	97.0	95.3	0.96
> 20°	3568	98.3	98.3	98.2	0.98

## Discussion

- Reliable post-processing method to overcome pernicious issue (30 years in the making!)
- Suggests an imaging setup for measuring kinematics slightly off-oblique to escape “ambiguous zone”

## Background

## Aims

Aim 1 - Joint Track Machine Learning

Aim 2 - Correcting Symmetric Implant Ambiguity

Aim 3 - Musings on a “Kinematics Translator” and Synthetic Kinematics Data

Aim 4 - This will definitely work on shoulders, right?

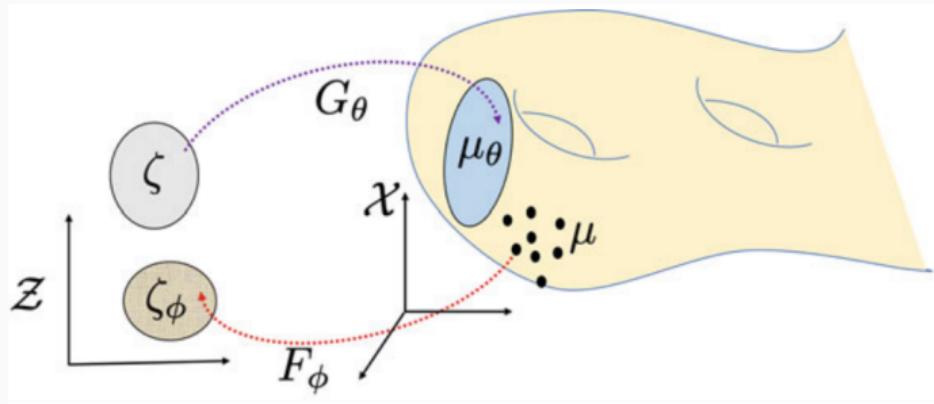
## Conclusion

## References

## A Kinematics Translator?

- We all understand the idea of translating a sentence (say, English) to a different language (say, French).
- If we imagine that a kinematics sequence during a specific movement (say, stair rise) is a “sentence”, could it be “translated” into the kinematics sequence from another movement (say, level walking)?
  - Could this reduce the total number of images needed for a clinical assessment?
  - The “meaning” of the sentence would, in theory, be that patients “kinematics fingerprint”.
  - Does that “kinematics fingerprint” contain within it information about:
    - Outcomes?
    - Joint pathologies?

# A High-Level Mathematical Framework



The geometry of generative models, from [31]

Common problems in machine learning can be viewed through this lens:

- Overfitting, bias (in the fairness sense), etc

## Not enough standardized kinematics data exists

1. Different research groups give the same name to different movements.
  - Squat, lunge, and kneel have no formal definition, and some groups' "squat" has the same qualities as other groups' "lunge".
2. There are no standardized set of movements to measure.
  - Not enough data per-patient to be able to create any robust generative model.
3. Different research groups have different data resolutions.
  - Some groups measure kinematics at every frame, others interpolate 0-30-60-90-120 flexion angles.
  - If the salient information is present, say, between 30-60 degrees flexion, then our latent space becomes filled with interpolations, rather than actual data.

## A path forward

With a fully-autonomous system for measuring kinematics, interested research groups have asked us which movements to measure. Should this move toward widespread clinical adoption, standards for “Kinematics Evaluations” can be established to homogenize data.

## Background

## Aims

Aim 1 - Joint Track Machine Learning

Aim 2 - Correcting Symmetric Implant Ambiguity

Aim 3 - Musings on a “Kinematics Translator” and Synthetic Kinematics Data

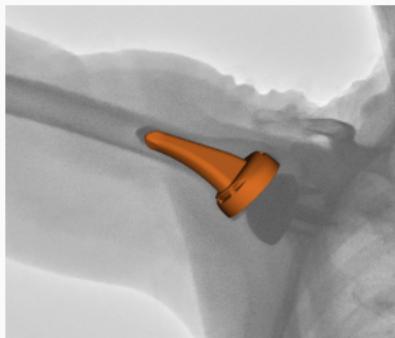
Aim 4 - This will definitely work on shoulders, right?

## Conclusion

## References

# Spoiler Alert

No, it won't.



## Goal

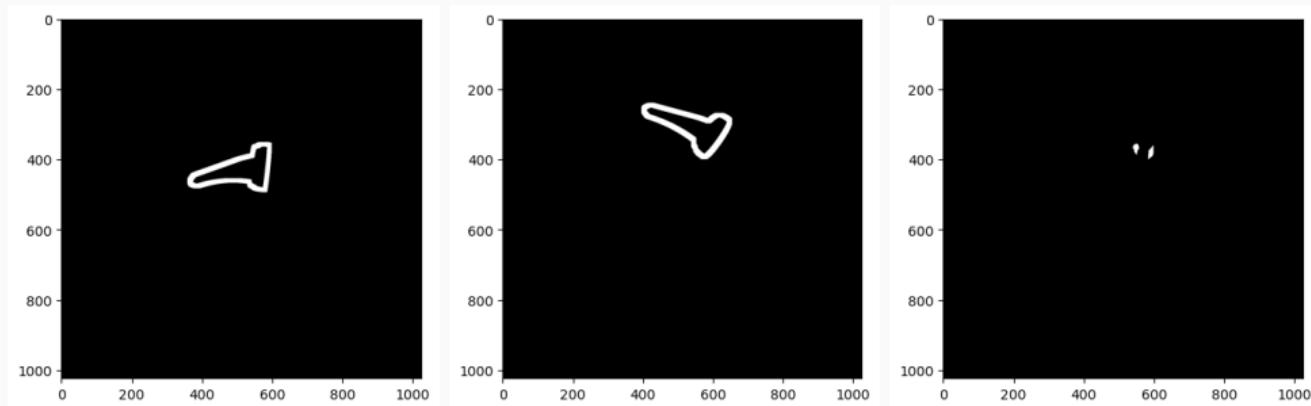
Establish a protocol for exploring the relative sensitivity of input orientation to projected shape

**Table 1:** Root mean squared differences between JointTrack Machine Learning optimized kinematics and manually registered kinematics on single-plane fluoroscopy

Implant Type	$x_{trans}(mm)$	$y_{trans}(mm)$	$z_{trans}(mm)$	$x_{rot}(\circ)$	$y_{rot}(\circ)$	$z_{rot}(\circ)$
Humeral	8.46	8.64	152.78	22.59	64.74	11.81
Glenosphere	0.97	1.44	32.58	13.72	26.40	8.30
Femoral	0.57	0.39	26.95	0.66	0.73	0.60
Tibial	0.67	0.64	27.17	1.63	2.74	0.66

# Improving Error Gradient

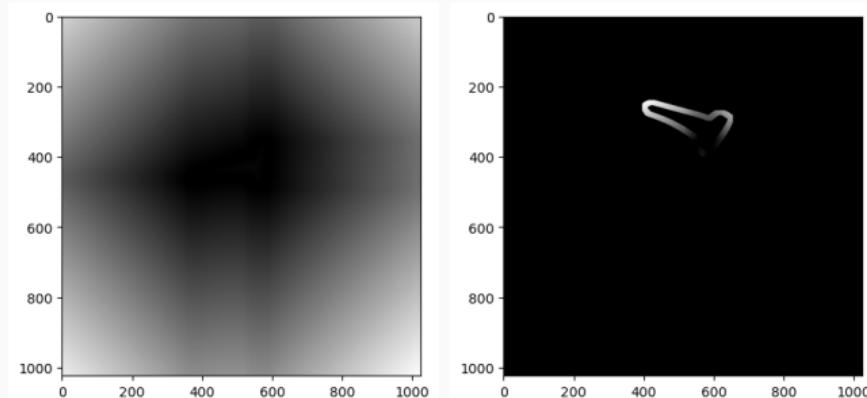
- Current cost function formulation (Hamming Distance) is not well suited to “near” and “far” estimates



## Modified Mean Surface Distance

- In order to improve error gradient, a modified mean surface distance was incorporated into the cost function.
- The mean of the dot product between the projection estimate and a distance map of the CNN segmentation.

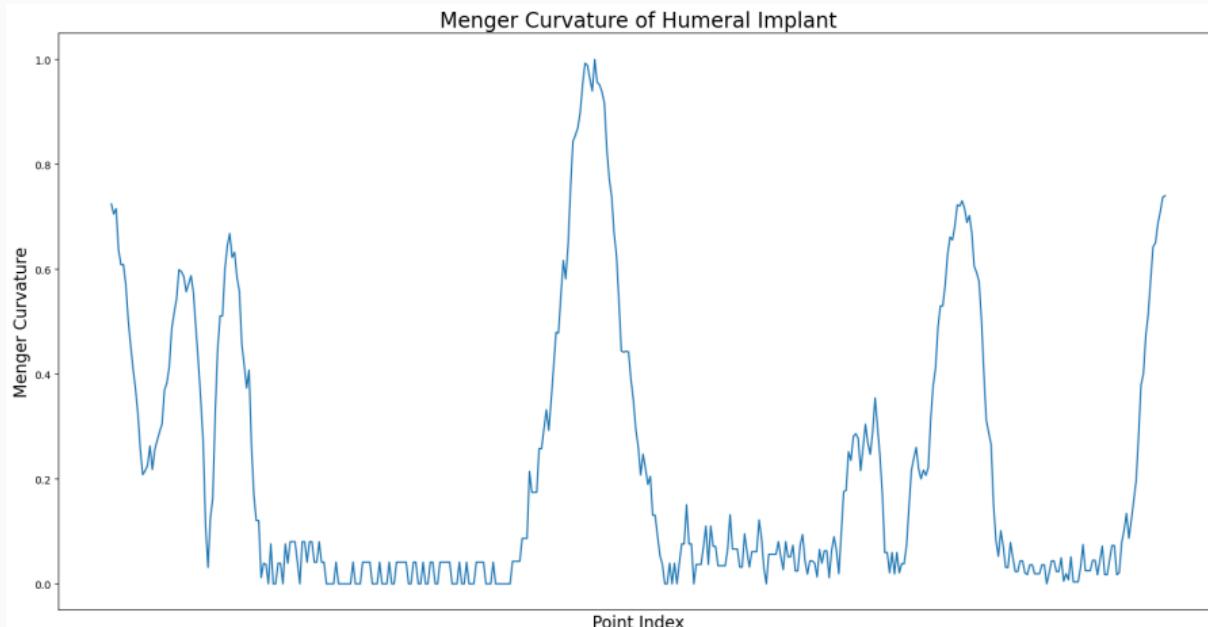
$$J = \frac{\text{Proj} \cdot DM}{\sum \text{Proj}} \quad (1)$$



It didn't work.

## Modified Asymmetric Keypoint Distance

- Early psychological research deemed curvature as highly salient for object recognition [32, 33]. This aimed to place additional emphasis on autonomously selected high-curvature regions.
  - Extracted regions of high-curvature using Menger's Algorithm [34].



## Modified Asymmetric Keypoint Distance

- Utilized a modified asymmetric surface distance on the discrete set of keypoints.

$$J = \frac{\sum_{k \in \mathbb{K}} (\min_{p \in \text{Proj}} (p \cdot DM_k))}{N_k}$$

where (2)

$\mathbb{K}$  = Set of all keypoints

$DM_k$  = Distance map for keypoint  $k$

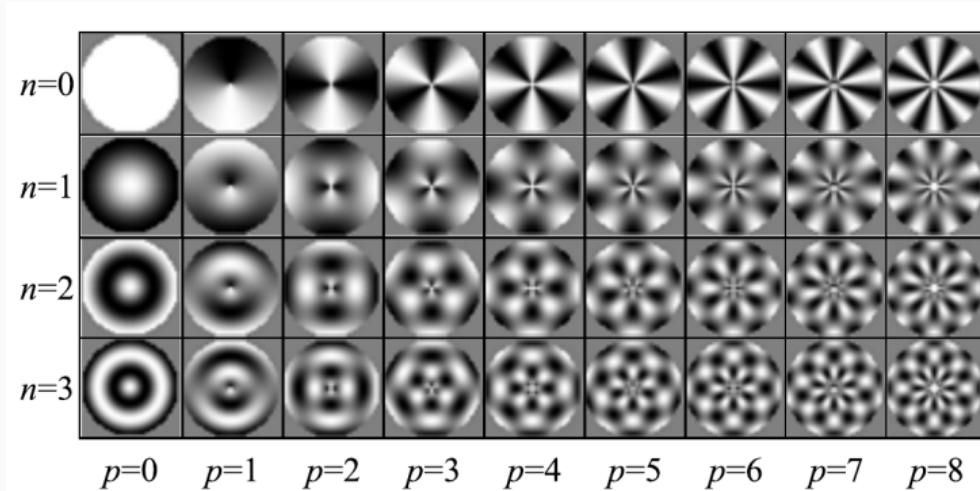
It didn't work...again.

## 2-Dimensional Shape

- **Shape descriptors** offer ways to describe shape numerically [35, 36].
  - A goal is for the “distance” between shapes to be smaller when the shapes are more “similar”.
- **Invariant Shape Descriptors** are immune to standard scaling and similarity transformations [37, 38].
  - Normalized Fourier Descriptors [39, 40, 41, 42, 8], Image Moments [43, 38], and many more.
  - This is much closer to a human-intuition of “shape”.

## Invariant Angular Radial Transform Descriptor

The Invariant Angular Radial Transform provides an orthogonal spatial basis function to describe binary images.



The basis “vectors” for the invariant angular radial transform. From [44].

## IARTD Feature Vector

The complex feature vector for IARTD is constructed to ensure orthogonality and rotational invariance for the magnitude. Prior to calculation, the image coordinates are normalized such that  $(0, 0)$  is at the center, and each of the four corners are  $(\pm 1, \pm 1)$ .

$$F_{np} = \int_0^{2\pi} \int_0^1 f(\rho, \theta) V_{np}(\rho, \theta) \rho d\rho d\theta \quad (3)$$

$f(\rho, \theta) \equiv$  Input image in polar coordinates

$$V_{np}(\rho, \theta) = \frac{1}{2\pi} e^{j p \theta} R_n(\rho) \quad (4)$$
$$R_n(\rho) = \begin{cases} 1 & n = 0 \\ 2 \cos(\pi n \rho) & n \neq 0 \end{cases}$$

## Normalizing IARTD Feature Vector

We normalize the phase of the feature vector to ensure full rotational invariance.

$$\begin{aligned}\phi'_{np} &= \phi_{np} - \phi_{n,1} \\ F'_{np} &= F_{np} e^{-jp\phi_{n,1}}\end{aligned}\tag{5}$$

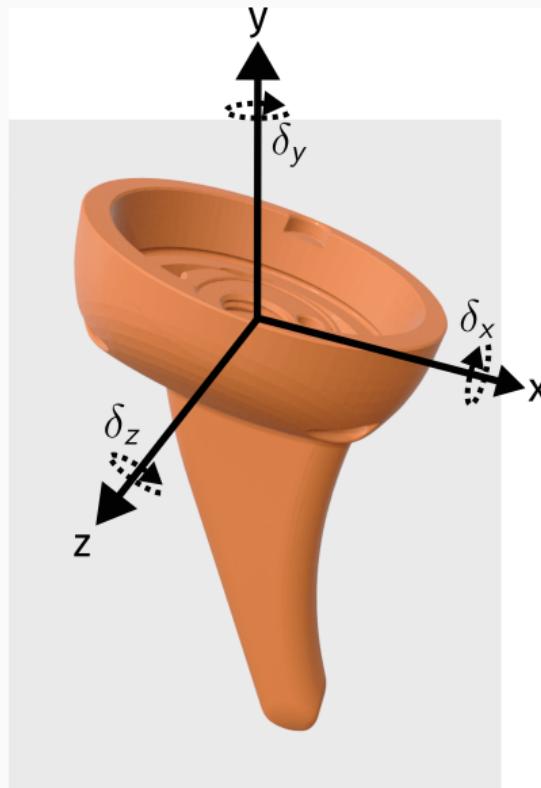
The final feature vector is constructed with the corrected phase and magnitude values. Values of  $p < 2$  are redundant and removed per the original authors' suggestion [44].

$$IARTD = \{|F'_{np}|, \phi'_{np}\} \text{ where } n \geq 0, p \geq 2 \tag{6}$$

## Methods - Shape Difference

The “input shapes” for each implant were the projected implants at  $\pm 30^\circ$  along each rotational axis at  $5^\circ$  increments.  $1^\circ$  perturbations were applied along each rotation axis.

$$\begin{aligned}\Delta S(\delta)_{z,x,y} \equiv & IARTD(R_{z,x,y,+\delta}) \\ & - IARTD(R_{z,x,y,-\delta}) \quad (7) \\ \forall \delta \in & \{\delta_x, \delta_y, \delta_z\}\end{aligned}$$



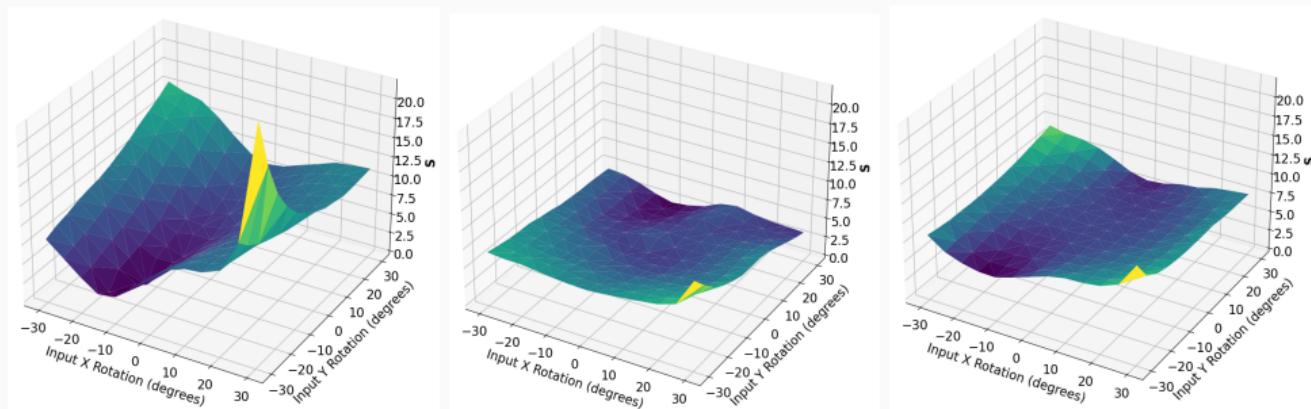
## Methods - Shape Sensitivity

The  $\Delta S(\delta)_{z,x,y}$  vector is normalized to account for overall scale of each element, in-plane rotation inputs are averaged, and the 2-norm of the difference vector is defined as the shape sensitivity.

A larger vector would indicate that the shape changed more for that particular “input shape” and perturbation.

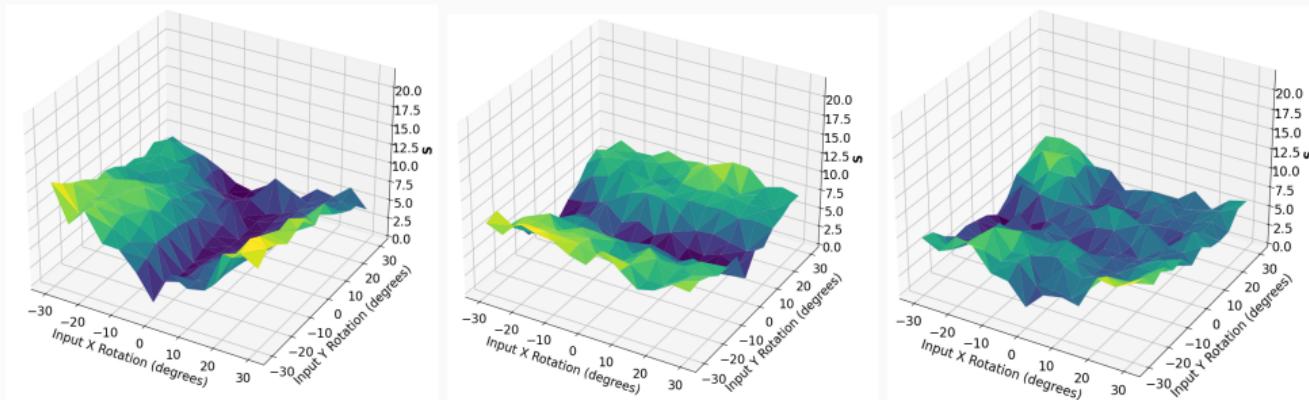
$$S(\delta)_{x,y} = \frac{\sum_z \|S(\delta)_{z,x,y}\|_2}{N} \quad (8)$$

## Results - Humeral Shape Sensitivity



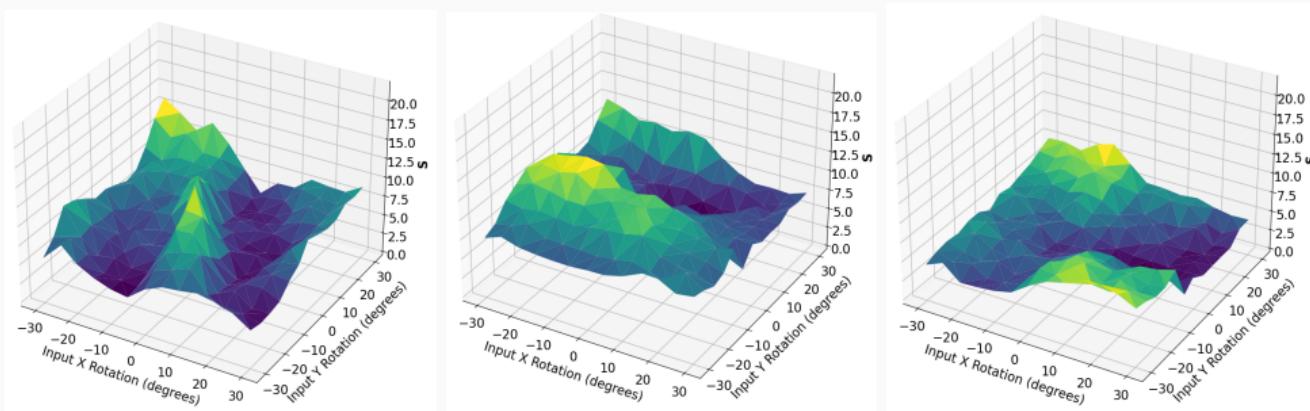
The  $\mathbb{S}$  plot for a humeral implant for  $\delta$  rotations along the x, y, and z axis, respectively.

## Results - Glenosphere Shape Sensitivity



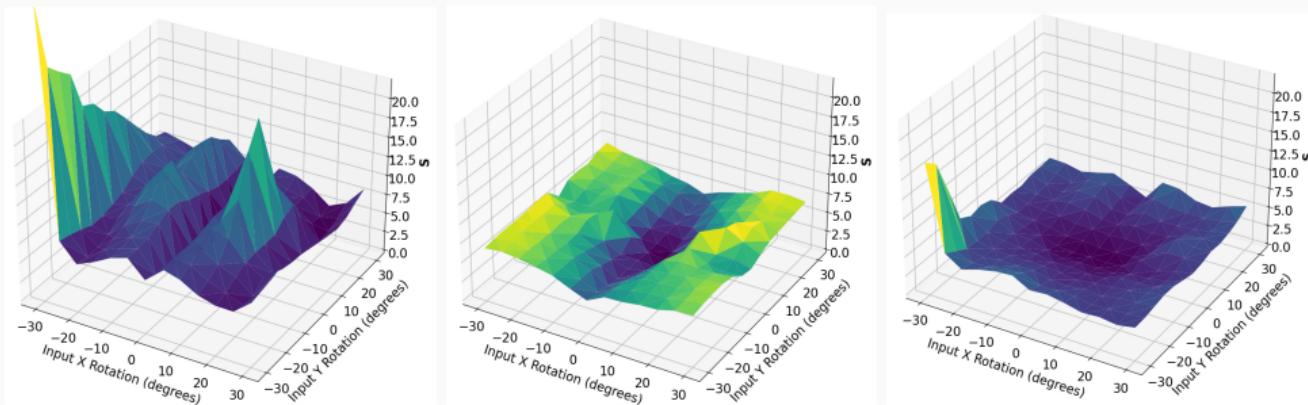
The  $\$$  plot for a glenosphere implant for  $\delta$  rotations along the x, y, and z axis, respectively.

## Results - Femoral Shape Sensitivity



The  $\$$  plot for a femoral implant for  $\delta$  rotations along the x, y, and z axis, respectively.

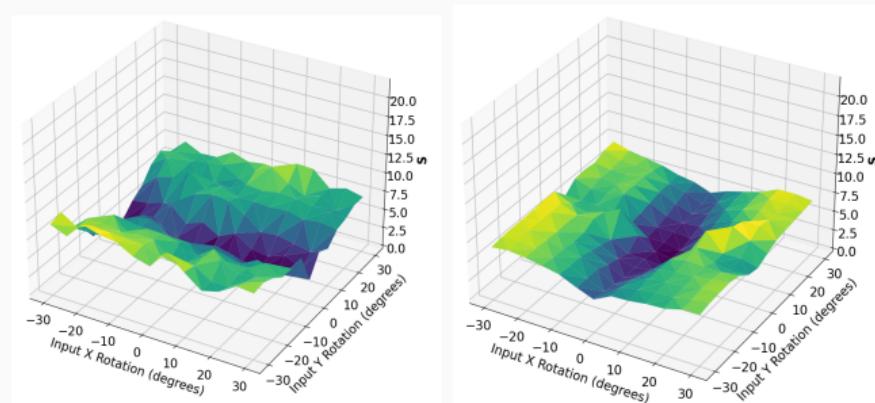
## Results - Tibial Shape Sensitivity



The  $\mathbb{S}$  plot for a tibial implant for  $\delta$  rotations along the x, y, and z axis, respectively.

## Key Takeaways

- Humeral implant has the lowest  $\delta_y$  sensitivity of all implants, which is the difficult registration axis.
- Tibial and glenosphere implants demonstrate a “valley” along rotation axis representing near-symmetry.
  - For tibial implants, this is the axis most commonly associated with “symmetry traps”.



Glenosphere (left) and tibial (right)  $\delta_y$  shape sensitivities.

## Next Steps

- Newer neural network
- Avoid regressing directly on Euler decompositions
  - Extruded map projections as  $SO(3)$  parametrization?
  - Gradient-free manifold optimization? (math nerds, please help)
- Bony-landmark information

## Conclusion

---

## Conclusions

Throughout the past four years, I have:

1. Established a fully autonomous method of measuring TKA kinematics from single plane fluoroscopy. This software is used globally by different research groups, and offers
2. Utilized machine learning to address “symmetry traps”, an inherent limitation in single-plane TKA kinematics measurements for nearly 30 years. Additionally, we offer an alternative imaging protocol for accurately measuring TKA kinematics in a clinical setting.
3. Developed a pipeline for accessing the relative performance of autonomous registration for different implants, conclusively finding that implant geometry alone is not sufficient for every joint.

## Presentations

---

- [1] Scott Banks, Andrew James Jensen, and Paris Flood. *In Regione Caecorum Rex Est Lucus - Towards Routine Clinical Examinations of Joint Kinematics.* Oslo, Norway, 2019.
- [2] Paris Flood, Andrew Jensen, and Scott Banks. *Towards Practical Clinical Examination of 3D Joint Kinematics Using Machine Learning.* Podium. Toronto, Ontario, 2019.
- [3] Andrew Jensen, Yifei Dai, and Andrea Gardner. *Impact of Sagittal Resection Variability on Implant Fit during Partial Knee Arthroplasty.* Podium. Phoenix, AZ, Feb. 2020.
- [4] Andrew Jensen et al. *Comparison of Clinical and Computational Implant Fit Analysis in Partial Knee Arthroplasty.* Podium. Phoenix, AZ, Feb. 2020.
- [5] Andrew Jensen et al. *Towards Routine Clinical Examination of 3D Joint Kinematics.* Korea, 2020.

## Presentations ii

- [6] Yifei Dai et al. *Comparative Analysis of Fixation Structure Design on the Primary Stability of Cementless TKA during Walking.* Podium. Online, Feb. 2021.
- [7] Yifei Dai et al. *Impact of Fixation Components on Primary Stability of Cementless TKA during Walking.* Podium. Online, Feb. 2021.
- [8] Andrew Jensen et al. *Accuracy of an Autonomous Method for Extracting Joint Kinematics from Single-Plane Fluoroscopy.* Oslo, Norway, 2021.
- [9] Andrew James Jensen et al. *An Autonomous Method for Extracting 3D Knee Replacement Kinematics from Dynamic Single Plane Fluoroscopic Images.* Online, 2021.
- [10] Jacob Griffith et al. *Automated Segmentation and Grading of Rodent Knee OA Histology Using Convolutional Neural Networks.* Poster. Tampa, FL, Feb. 2022.
- [11] Andrew Jensen, Lindsey Palm, and Scott Banks. *Autonomous Measurement of 3D TKA Kinematics from Dynamic Single-Plane Fluoroscopic Images.* Podium. Tampa, FL, Feb. 2022.
- [12] Andrew Jensen. *Deep Learning for Image Processing in Orthopaedics.* Virtual Scientific Session. Online, Jan. 2023.

## Presentations iii

- [13] Andrew J. Jensen et al. *Overcoming Single-Plane Limitations in TKA Kinematics Measurements Using Machine Learning*. Podium. New York, NY, Sept. 2023.

## Publications

---

- [1] William Burton et al. “Automatic Tracking of Healthy Joint Kinematics from Stereo-Radiography Sequences.”. In: *Computers in Biology and Medicine* (2021). DOI: [10.1016/j.combiomed.2021.104945](https://doi.org/10.1016/j.combiomed.2021.104945).
- [2] Jordan S. Broberg et al. “Validation of a Machine Learning Technique for Segmentation and Pose Estimation in Single Plane Fluoroscopy”. In: *Journal of Orthopaedic Research* (Feb. 2023). DOI: [10.1002/jor.25518](https://doi.org/10.1002/jor.25518).
- [3] Andrew J. Jensen et al. “Joint Track Machine Learning: An Autonomous Method of Measuring Total Knee Arthroplasty Kinematics From Single-Plane X-Ray Images”. In: *The Journal of Arthroplasty* 38.10 (May 2023), pp. 2068–2074. DOI: [10.1016/j.arth.2023.05.029](https://doi.org/10.1016/j.arth.2023.05.029).

## Timeline

Date(s)	Event
2015-2019	Mech. Eng. B.S, Magna Cum Laude, UF
April 2019 - April 2020	Internship at Exactech
April 2020	Started in Miller Lab
August 2020	Officially Started PhD at UF
November 2021	Best Presentation Award at ISTA: Emerging Technologies
September 2022	HAP Paul Award at ISTA 2022
November 2023	Symmetry Trap Paper Submitted
December 2023	Part-time Internship at Exactech Started
February 2024	Revisions Requested for Symmetry Trap Paper
March 2024	Implant Shape Sensitivity Paper Submitted
March 2024	Revised Symmetry Trap Paper Submitted

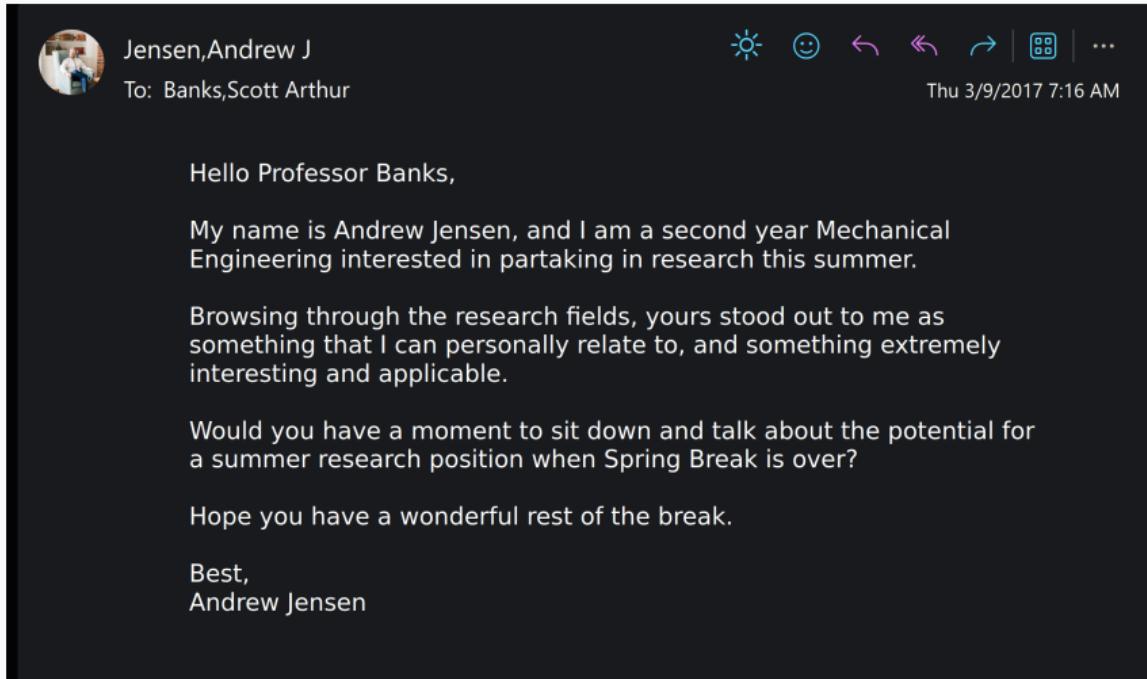
## A Special Thanks

- Dr. Scott Banks
- Drs. Kerry Costello, Catia Silva,  
Jessica Allen, Jennifer Nichols
- The whole Gary J. Miller Lab Crew
  - Paris Flood, Xheni Bare, Lindsey  
Palm-Vlasak, Sasank Desaraju,  
Duloc He, Noah Davis
  - Nicholas Verdugo, Daniel Torrejon,  
Stefan Kieszkowski
- Lauren Jensen
- Robin and Erik Jensen

# Thank you!

Thanks for listening!!

Any Questions?



The screenshot shows an email interface with a dark theme. At the top left is a circular profile picture of a man. To its right is the recipient's name, "Jensen, Andrew J". Below that is the "To:" field, "Banks, Scott Arthur". On the far right are several small, light-colored icons: a sun-like symbol, a smiley face, a left arrow, a double-left arrow, a double-right arrow, a right arrow, a square with a grid, and three dots. Further down, the date and time are displayed as "Thu 3/9/2017 7:16 AM". The main body of the email contains the following text:

Hello Professor Banks,

My name is Andrew Jensen, and I am a second year Mechanical Engineering interested in partaking in research this summer.

Browsing through the research fields, yours stood out to me as something that I can personally relate to, and something extremely interesting and applicable.

Would you have a moment to sit down and talk about the potential for a summer research position when Spring Break is over?

Hope you have a wonderful rest of the break.

Best,  
Andrew Jensen

## References

---

## References

---

- [1] Steven Kurtz et al. “**Projections of Primary and Revision Hip and Knee Arthroplasty in the United States from 2005 to 2030:**” in: *The Journal of Bone & Joint Surgery* 89.4 (Apr. 2007), pp. 780–785. DOI: 10.2106/JBJS.F.00222.
- [2] P. N. Baker et al. “**The Role of Pain and Function in Determining Patient Satisfaction After Total Knee Replacement: Data From the National Joint Registry for England and Wales**”. In: *The Journal of Bone and Joint Surgery. British volume* 89-B.7 (July 2007), pp. 893–900. DOI: 10.1302/0301-620X.89B7.19091.
- [3] Robert B. Bourne et al. “**Patient Satisfaction after Total Knee Arthroplasty: Who Is Satisfied and Who Is Not?**” In: *Clinical Orthopaedics & Related Research* 468.1 (Jan. 2010), pp. 57–63. DOI: 10.1007/s11999-009-1119-9.

## References ii

- [4] C. E. H. Scott et al. “Predicting Dissatisfaction Following Total Knee Replacement: A Prospective Study of 1217 Patients”. In: *The Journal of Bone and Joint Surgery. British volume* 92-B.9 (Sept. 2010), pp. 1253–1258. DOI: 10.1302/0301-620X.92B9.24394.
- [5] M.R. Mahfouz et al. “A Robust Method for Registration of Three-Dimensional Knee Implant Models to Two-Dimensional Fluoroscopy Images”. In: *IEEE Transactions on Medical Imaging* 22.12 (Dec. 2003), pp. 1561–1574. DOI: 10.1109/TMI.2003.820027.
- [6] S. Zuffi et al. “A Model-Based Method for the Reconstruction of Total Knee Replacement Kinematics”. In: *IEEE Transactions on Medical Imaging* 18.10 (Oct./1999), pp. 981–991. DOI: 10.1109/42.811310.
- [7] S. Lavallee and R. Szeliski. “Recovering the Position and Orientation of Free-Form Objects from Image Contours Using 3D Distance Maps”. In: *IEEE Transactions on Pattern Analysis and Machine Intelligence* 17.4 (Apr. 1995), pp. 378–390. DOI: 10.1109/34.385980.

## References iii

- [8] S.A. Banks and W.A. Hodge. “Accurate Measurement of Three-Dimensional Knee Replacement Kinematics Using Single-Plane Fluoroscopy”. In: *IEEE Transactions on Biomedical Engineering* 43.6 (June 1996), pp. 638–649. DOI: [10.1109/10.495283](https://doi.org/10.1109/10.495283).
- [9] Bo Gao and Naiquan (Nigel) Zheng. “Investigation of Soft Tissue Movement during Level Walking: Translations and Rotations of Skin Markers”. In: *Journal of Biomechanics* 41.15 (Nov. 2008), pp. 3189–3195. DOI: [10.1016/j.jbiomech.2008.08.028](https://doi.org/10.1016/j.jbiomech.2008.08.028).
- [10] Mei-Ying Kuo et al. “Influence of Soft Tissue Artifacts on the Calculated Kinematics and Kinetics of Total Knee Replacements during Sit-to-Stand”. In: *Gait & Posture* 33.3 (Mar. 2011), pp. 379–384. DOI: [10.1016/j.gaitpost.2010.12.007](https://doi.org/10.1016/j.gaitpost.2010.12.007).
- [11] Cheng-Chung Lin et al. “Effects of Soft Tissue Artifacts on Differentiating Kinematic Differences between Natural and Replaced Knee Joints during Functional Activity”. In: *Gait & Posture* 46 (May 2016), pp. 154–160. DOI: [10.1016/j.gaitpost.2016.03.006](https://doi.org/10.1016/j.gaitpost.2016.03.006).

- [12] Mario A. Lafortune et al. “Three-Dimensional Kinematics of the Human Knee during Walking.”. In: *Journal of Biomechanics* (1992). DOI: 10.1016/0021-9290(92)90254-x.
- [13] John C. Ivester et al. “A Reconfigurable High-Speed Stereo-Radiography System for Sub-Millimeter Measurement of In Vivo Joint Kinematics”. In: *Journal of Medical Devices* 9.4 (Dec. 2015), p. 041009. DOI: 10.1115/1.4030778.
- [14] William Burton et al. “Automatic Tracking of Healthy Joint Kinematics from Stereo-Radiography Sequences.”. In: *Computers in Biology and Medicine* (2021). DOI: 10.1016/j.combiomed.2021.104945.
- [15] P. D. L. Flood and Scott A. Banks. “Automated Registration of 3-D Knee Implant Models to Fluoroscopic Images Using Lipschitzian Optimization”. In: *IEEE Transactions on Medical Imaging* 37.1 (2018), pp. 326–335. DOI: 10.1109/tmi.2017.2773398.
- [16] Henri A Vrooman et al. “Fast and Accurate Automated Measurements in Digitized Stereophotogrammetric Radiographs”. In: *Journal of Biomechanics* 31.5 (May 1998), pp. 491–498. DOI: 10.1016/S0021-9290(98)00025-6.

- [17] Göran Selvik. “Roentgen Stereophotogrammetry: A Method for the Study of the Kinematics of the Skeletal System”. In: *Acta Orthopaedica Scandinavica* 60.sup232 (Jan. 1989), pp. 1–51. DOI: [10.3109/17453678909154184](https://doi.org/10.3109/17453678909154184).
- [18] B L Kaptein et al. “Evaluation of Three Pose Estimation Algorithms for Model-Based Roentgen Stereophotogrammetric Analysis”. In: *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine* 218.4 (Apr. 2004), pp. 231–238. DOI: [10.1243/0954411041561036](https://doi.org/10.1243/0954411041561036).
- [19] Tuuli Saari et al. “Knee Kinematics in Medial Arthroscopy. Dynamic Radiostereometry during Active Extension and Weight-Bearing”. In: *Journal of Biomechanics* 38.2 (Feb. 2005), pp. 285–292. DOI: [10.1016/j.jbiomech.2004.02.009](https://doi.org/10.1016/j.jbiomech.2004.02.009).
- [20] Jordan S. Broberg et al. “Validation of a Machine Learning Technique for Segmentation and Pose Estimation in Single Plane Fluoroscopy”. In: *Journal of Orthopaedic Research* (Feb. 2023). DOI: [10.1002/jor.25518](https://doi.org/10.1002/jor.25518).
- [21] Andrew J. Jensen et al. “Joint Track Machine Learning: An Autonomous Method of Measuring Total Knee Arthroplasty Kinematics From Single-Plane X-Ray Images”. In: *The Journal of Arthroplasty* 38.10 (May 2023), pp. 2068–2074. DOI: [10.1016/j.arth.2023.05.029](https://doi.org/10.1016/j.arth.2023.05.029).

- [22] Jingdong Wang et al. “**Deep High-Resolution Representation Learning for Visual Recognition**”. In: *arXiv:1908.07919 [cs]* (Mar. 2020). arXiv: 1908.07919 [cs].
- [23] Alexander Buslaev et al. “**Albumentations: Fast and Flexible Image Augmentations**”. In: *Information* 11.2 (Feb. 2020), p. 125. doi: 10.3390/info11020125.
- [24] Charles Audet and Warren Hare. ***Derivative-Free and Blackbox Optimization***. Springer Series in Operations Research and Financial Engineering. Cham: Springer International Publishing, 2017. doi: 10.1007/978-3-319-68913-5.
- [25] Ishan Bajaj, Akhil Arora, and M. M. Faruque Hasan. “**Black-Box Optimization: Methods and Applications**”. In: (Jan. 2021), pp. 35–65. doi: 10.1007/978-3-030-66515-9\_2.
- [26] Bruno O. Shubert. “**A Sequential Method Seeking the Global Maximum of a Function**”. In: *SIAM Journal on Numerical Analysis* 9.3 (1972), pp. 379–388. doi: 10.1137/0709036. eprint: <https://doi.org/10.1137/0709036>.
- [27] R.L. Graham. “**An Efficient Algorithm for Determining the Convex Hull of a Finite Planar Set**”. In: *Information Processing Letters* 1.4 (June 1972), pp. 132–133. doi: 10.1016/0020-0190(72)90045-2.

- [28] R A Jarvis. “On the Identification of the Convex Hull of a Finite Set of Points in the Plane”. In: (1973).
- [29] T. M. Chan. “Optimal Output-Sensitive Convex Hull Algorithms in Two and Three Dimensions”. In: *Discrete & Computational Geometry* 16.4 (Apr. 1996), pp. 361–368. DOI: 10.1007/BF02712873.
- [30] C. Bradford Barber, David P. Dobkin, and Hannu Huhdanpaa. “The Quickhull Algorithm for Convex Hulls”. In: *ACM Transactions on Mathematical Software* 22.4 (Dec. 1996), pp. 469–483. DOI: 10.1145/235815.235821.
- [31] Jong Chul Ye. *Geometry of Deep Learning: A Signal Processing Perspective*. Vol. 37. Mathematics in Industry. Singapore: Springer Nature Singapore, 2022. DOI: 10.1007/978-981-16-6046-7.
- [32] Fred Attneave. “Some Informational Aspects of Visual Perception.”. In: *Psychological Review* 61.3 (1954), pp. 183–193. DOI: 10.1037/h0054663.
- [33] Fred Attneave and Malcolm D. Arnoult. “The Quantitative Study of Shape and Pattern Perception.”. In: *Psychological Bulletin* 53.6 (Nov. 1956), pp. 452–471. DOI: 10.1037/h0044049.

- [34] J. C. Léger. *Menger Curvature and Rectifiability*. Apr. 1999. arXiv: [math/9905212](https://arxiv.org/abs/math/9905212).
- [35] Dengsheng Zhang and Guojun Lu. “Review of Shape Representation and Description Techniques”. In: *Pattern Recognition* 37.1 (Jan. 2004), pp. 1–19. DOI: [10.1016/j.patcog.2003.07.008](https://doi.org/10.1016/j.patcog.2003.07.008).
- [36] J Flusser. “Invariant Shape Description and Measure of Object Similarity”. In: *International Conference on Image Processing and Its Applications*. 1992.
- [37] David G. Lowe. “Distinctive Image Features from Scale-Invariant Keypoints”. In: *International Journal of Computer Vision* 60.2 (Nov. 2004), pp. 91–110. DOI: [10.1023/B:VISI.0000029664.99615.94](https://doi.org/10.1023/B:VISI.0000029664.99615.94).
- [38] Alireza Khotanzad and Y.H. Hong. “Invariant Image Recognition by Zernike Moments”. In: *IEEE Transactions on Pattern Analysis and Machine Intelligence* 12.5 (May 1990), pp. 489–497. DOI: [10.1109/34.55109](https://doi.org/10.1109/34.55109).
- [39] Eric Persoon and King-Sun Fu. “Shape Discrimination Using Fourier Descriptors”. In: 7.3 (Mar. 1977), pp. 170–179. DOI: [10.1109/tsmc.1977.4309681](https://doi.org/10.1109/tsmc.1977.4309681).

- [40] C. C. Lin and R. Chellappa. “Classification of Partial 2-D Shapes Using Fourier Descriptors”. In: *IEEE Transactions on Pattern Analysis and Machine Intelligence* PAMI-9.5 (Sept. 1987), pp. 686–690. DOI: [10.1109/TPAMI.1987.4767963](https://doi.org/10.1109/TPAMI.1987.4767963).
- [41] Timothy P. Wallace and Paul A. Wintz. “An Efficient Three-Dimensional Aircraft Recognition Algorithm Using Normalized Fourier Descriptors”. In: *Computer Graphics and Image Processing* 13.2 (Jan. 1980), pp. 99–126. DOI: [10.1016/S0146-664X\(80\)80035-9](https://doi.org/10.1016/S0146-664X(80)80035-9).
- [42] Timothy P. Wallace and Owen R. Mitchell. “Analysis of Three-Dimensional Movement Using Fourier Descriptors”. In: *IEEE Transactions on Pattern Analysis and Machine Intelligence* PAMI-2.6 (1980), pp. 583–588. DOI: [10.1109/TPAMI.1980.6447707](https://doi.org/10.1109/TPAMI.1980.6447707).
- [43] Whoi-Yul Kim and Yong-Sung Kim. “A Region-Based Shape Descriptor Using Zernike Moments”. In: *Signal Processing-image Communication* 16.1 (Sept. 2000), pp. 95–102. DOI: [10.1016/s0923-5965\(00\)00019-9](https://doi.org/10.1016/s0923-5965(00)00019-9).
- [44] Jong-Min Lee and Whoi-Yul Kim. “A New Shape Description Method Using Angular Radial Transform”. In: *IEICE Transactions on Information and Systems* E95.D.6 (2012), pp. 1628–1635. DOI: [10.1587/transinf.E95.D.1628](https://doi.org/10.1587/transinf.E95.D.1628).