

# Joint Track Machine Learning

---

Andrew Jensen

March 9, 2023

Introduction

Motivation

Background

Historical Methods

Aims

References

# Introduction

---

# Acknowledgments

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

# Motivation

---

# The Problem

- Joints manifest pain during dynamic activity.
- 20% of patients receiving TKA are dissatisfied.
  - Instability, pain, unnatural [1, 3, 15].
- No reliable method of clinically assessing and quantifying joint dynamics.
  - Too much human supervision, too time consuming



# Our Proposition

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

**Rx PRESCRIPTION**

NAME Knee McHurty AGE Old  
ADDRESS \_\_\_\_\_ DATE \_\_\_\_\_

**Dynamic Knee Study**

- Walking
- Sit-to-stand
- Kneeling
- Stairs

☐ LABEL  
REFILL 0 1 2 4 5 PRN

Health

# 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

---

## Homogeneous Transformation Matrix

$$T_B^A = \begin{pmatrix} R_B^A & P_{B,origin}^A \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

## Rotation Matrices

$$R_x = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_x & -s_x \\ 0 & s_x & c_x \end{pmatrix}$$

$$R_y = \begin{pmatrix} s_y & 0 & c_y \\ 0 & 1 & 0 \\ c_y & 0 & -s_y \end{pmatrix}$$

$$R_z = \begin{pmatrix} c_z & -s_z & 0 \\ s_z & c_z & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

## Translation

$$\begin{pmatrix} v'_x \\ v'_y \end{pmatrix} = \begin{pmatrix} v_x \\ v_y \end{pmatrix} + \begin{pmatrix} t_x \\ t_y \end{pmatrix}$$

$\rightarrow$

$$\begin{pmatrix} v'_x \\ v'_y \\ 1 \end{pmatrix} = \begin{pmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} v_x \\ v_y \\ 1 \end{pmatrix}$$

## Rotations

$$R_x = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_x & -s_x \\ 0 & s_x & c_x \end{pmatrix}$$

$$R_y = \begin{pmatrix} s_y & 0 & c_y \\ 0 & 1 & 0 \\ c_y & 0 & -s_y \end{pmatrix}$$

$$R_z = \begin{pmatrix} c_z & -s_z & 0 \\ s_z & c_z & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

## Homogeneous Transformation Matrices

$$\begin{aligned}\vec{v}' &= \begin{pmatrix} R_{3 \times 3} & \vec{t}_{3 \times 1} \\ 0 & 1 \end{pmatrix} \tilde{v} \\ &= T_B^A \tilde{v}\end{aligned}$$

Now we have a notation that allows us to describe arbitrary movement between reference frames.

# Projective Geometry

$$\begin{pmatrix} x_s \\ y_s \\ z_s \\ 1 \end{pmatrix}_i = T_{scene}^{cam} \tilde{p}_i^{obj}$$

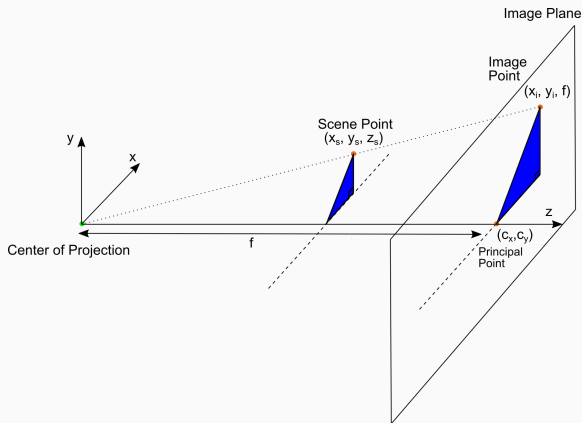
$$\begin{pmatrix} \tilde{x}_{img} \\ \tilde{y}_{img} \\ \tilde{z} \\ 1 \end{pmatrix} = \begin{pmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{pmatrix} \vec{x}_s$$

Where

$$x_{img} = \frac{\tilde{x}_{img}}{\tilde{z}} = \frac{f}{z_s} x_s$$

$$y_{img} = \frac{\tilde{y}_{img}}{\tilde{z}} = \frac{f}{z_s} y_s$$

Note: We are still in the camera's reference frame



Convert camera coordinates into image coordinates.

$$p_x = k_x x_{img} + c_x$$

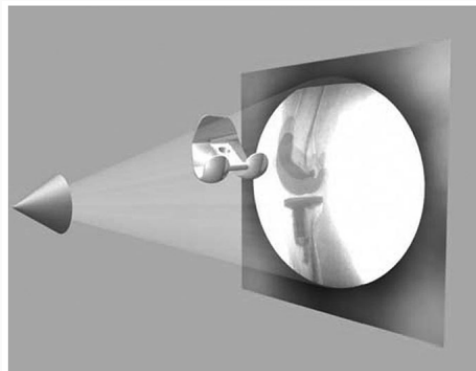
$$p_y = k_y y_{img} + c_y$$

Where

$k \equiv$  Pixel Spacing

$c \equiv$  Image Focal Point

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 [13]



# Historical Methods

---

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

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

# Pre-Computed Projections

- Saving space and memory by pre-computing as much as possible.
- Pre-computed distance maps [17, 11].
- Pre-computed shape libraries [2]

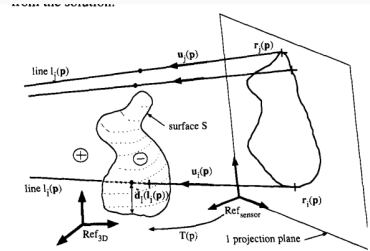
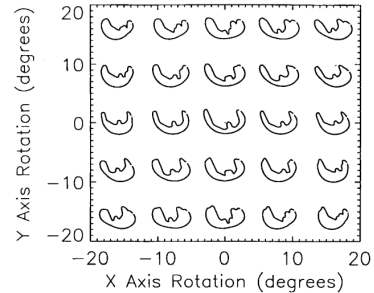


Fig. 2. Projection line to surface distance computation.

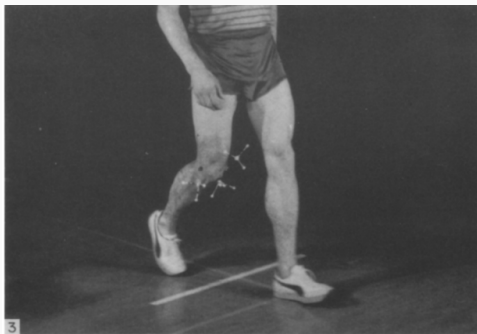
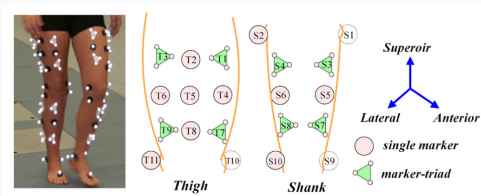


# Limitations of Pre-Computed Projections

- Requires an accurate contour from the input image in order to perform calculations.
  - Human supervision vs. inaccuracy.

# Motion Capture (MoCap)

- Can measure motion of MoCap beads very accurately.
- Skin-mounted [6, 9, 12].
- Bone pins [10] (any volunteers?).



# Limitations of Motion Capture

## Skin Mounted

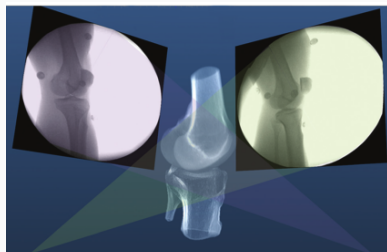
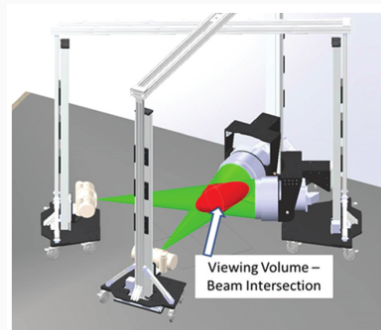
- Doesn't accurately describe underlying skeletal motion with clinical accuracy [6, 9, 12].

## Bone Pins

- Bone Pins
- Need I say more?

# Biplane Imaging

- Utilizes multiple cameras to resolve 3D position and orientation[7, 5].
  - Highly accurate.
  - Gold Standard.



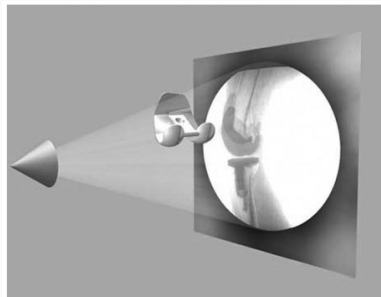
# Limitations of Biplane Imaging

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



# Iterative Projections

- Take advantage of modern computational graphics pipelines to quickly perform projection matching.
- Image/Intensity similarity metrics [13]
- Feature/Contour similarity metrics



# Limitations of (historic) Iterative Projection Methods

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

# Model-based Roentgen Stereophotogrammetry (MBRSA)

- Uses implanted tantalum beads for motion tracking [16]
- Extremely accurate [8, 14]
- Gold standard Measurement [4]
- Involves additional surgical procedures for inserting tantalum beads
- Human supervision
- Typically requires bi-plane imaging.

## Aims

---

## **Aims 1/2**

Joint Track Machine

Learning and Overcoming

Single-Plane Limitations

## **Aim 3/4**

Pilot Trials and

Standardized Kinematics

Exam

## **Aim 5**

Joint Track Auto Toolkit

## References

---

## References

---

- [1] 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. ISSN: 0301-620X, 2044-5377. DOI: 10.1302/0301-620X.89B7.19091.
- [2] 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. ISSN: 00189294. DOI: 10.1109/10.495283.
- [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. ISSN: 0009-921X. DOI: 10.1007/s11999-009-1119-9.

- [4] 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), jor.25518. ISSN: 0736-0266, 1554-527X. DOI: 10.1002/jor.25518.
- [5] 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.
- [6] 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. ISSN: 00219290. DOI: 10.1016/j.jbiomech.2008.08.028.
- [7] 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. ISSN: 1932-6181, 1932-619X. DOI: 10.1115/1.4030778.



- [8] 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. ISSN: 0954-4119, 2041-3033. DOI: 10.1243/0954411041561036.
- [9] 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. ISSN: 09666362. DOI: 10.1016/j.gaitpost.2010.12.007.
- [10] 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.
- [11] 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. ISSN: 01628828. DOI: 10.1109/34.385980.

- [12] 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. ISSN: 09666362. DOI: 10.1016/j.gaitpost.2016.03.006.
- [13] 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. ISSN: 0278-0062. DOI: 10.1109/TMI.2003.820027.
- [14] Tuuli Saari et al. **“Knee Kinematics in Medial Arthrosis. Dynamic Radiostereometry during Active Extension and Weight-Bearing”**. In: *Journal of Biomechanics* 38.2 (Feb. 2005), pp. 285–292. ISSN: 00219290. DOI: 10.1016/j.jbiomech.2004.02.009.
- [15] 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. ISSN: 0301-620X, 2044-5377. DOI: 10.1302/0301-620X.92B9.24394.

- [16] 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. ISSN: 0001-6470. DOI: 10.3109/17453678909154184.
- [17] 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. ISSN: 02780062. DOI: 10.1109/42.811310.